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Research with the Waveguide Beyond Cutoff or Separated Aperture Dielectric Anomaly Detection Scheme

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This report presents experimental results concerning the separated aperture (or waveguide beyond cutoff) buried mine detection scheme. The primary purpose of this research effort is to contribute to an engineering database to be used in a long term research program directed toward the development of a complete understanding of the fundamental electromagnetic principles underlying the separated aperture mine detection technique and to assess the general feasibility of separated aperture mine detectors. KEYWORDS: LAND MINES; MINE DETECTION. (RH)

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SECTION I. INTRODUCTION

FUNDAMENTAL OPERATING PRINCIPLES OF THE WAVEGUIDE BEYOND CUTOFF BURIED MINE DETECTION SCHEME

Figure 1 (see Appendix A) shows a simplified representation of the separated aperture or waveguide beyond cutoff mine detection scheme. As shown, the sensor is composed of a transmit and receive dipole pair separated by a metallic septum. Each dipole resides within a corner reflector. For a fixed input power, the output power measured at the receiving dipole is monitored. As the sensor head moves over the surface of the earth, the received power varies. When the sensor head is over uniform background (no mine present) very little power is received. There is a significant increase in received power when the sensor head is over a mine.

Although the separated aperture approach to mine detection is simple, it has certain, very desirable features that are not shared by other electromagnetic mine detection methods. Electromagnetic identification of buried mines requires a transmitter and receiver: energy from the transmitter penetrates the earth surface, interacts with the buried mine, and is then coupled into the receiver for detection. Unfortunately, a rather large amount of energy can be directly coupled from transmitter to receiver or reflected from the air-soil interface and coupled into the receiver. Energy at the receiver which interacts with the mine (the signal) can be quite small in comparison with this direct and ground reflected energy (the clutter). The advantage of the separated aperture approach over other electromagnetic detection techniques is that, under proper operating conditions, the direct and ground reflected signals are substantially suppressed in comparison with the return from the buried mine. The metallic septum forms a waveguide with the earth's surface and when the septum-earth separation is small, this waveguide is below cutoff resulting in an exponential attenuation of the direct and ground reflected signals and a vastly improved signal-to-clutter ratio. In fact, according to one source, the waveguide beyond cutoff sensor exhibited the best signal-to-clutter ratio of any technique ever attempted.[1]

HISTORICAL PERSPECTIVE

As discussed in the report, *MERADCOM Mine Detection Program: 1960-1980:*

> "The waveguide beyond cutoff concept was discovered in the 50's and implemented in a portable (hand held) mine detector, the PRS-6, which was never type classified. Experimental data collected under controlled conditions exhibited the best signal-to-clutter ratio of any technique ever attempted, and tests against the PRS-4 revealed it to be superior in both detection and false-alarm rejection. Its major drawback was its height sensitivity which produced a false alarm signal when the antenna reached a height of one-half wavelength. The PRS-4 and PRS-7, which had lower detection capability, merely ceased to detect without alarm and had, therefore, greater user acceptance."[1]

Research leading to a vehicular-mounted road mine detection system based on the separated aperture approach was conducted from the early 1970s to April 1982. The development effort was undertaken by the Belvoir RD&E Center with technical support from the National Bureau of Standards (NBS) (now the National Institute of Standards and Technology (NIST)) and the Cubic Corporation. According to Report 2412, *Vehicle-Mounted Road Mine Detector System (VMRMDS), AN/VRS-5:*

> "Concentrated investigative efforts were conducted by the Bureau of Standards in the antenna design and frequency determinations. The Cubic Corporation was contracted to proceed in the tasks of electronic signal transposing for field use and mechanical development for vehicle-mounted field use." [2]

A Vehicle-Mounted Road Mine Detection System (VMRMDS), AN/VRS-5, shown in Figure 2 (see Appendix A), was eventually constructed and subjected to Operational Testing (OTII) by the Armor and Engineer Board at Fort Knox, KY, between January and April 1982. Many system deficiencies were noted during this test, the most serious of which was the extremely poor mine detection rates of mines buried in high-moisture content soils and mines subjected to vehicle wheel or tread compaction. Again, according to Report 2412:

> "During the same time period (between January and April 1982), TRADOC determined that there was no longer a requirement for a vehicle-mounted mine detector which could be used only on roads or other flat terrain. By letter US Army Engineer School (TRADOC proponent), ATZA-CDM, 9 April 1984, withdrew the requirement for the system causing DARCOM (now AMC) to direct termination of the program." [2]

LESSONS LEARNED AND ISSUES RAISED

Although the VMRMDS previously discussed was never accepted by the Army, the separated aperture approach to mine detection, for reasons outlined above, is nevertheless considered by knowledgeable individuals at the Belvoir RD&E Center to be one of the best mine-detection schemes ever developed both in terms of detection reliability and false-alarm rejection. The technique is, however, limited to relatively level, sparsely vegetated terrain since the septum earth separation must be small to achieve the waveguide below cutoff effect discussed above.

Much was learned from past theoretical and experimental research efforts with the separated aperture mine detection technique. However, the eventual failure of the AN/VRS-5 exposed several important limitations that must be addressed before another full scale development program can be pursued. Some of the more important issues which must be resolved are as follows:

1 A mine buried in soil with high moisture content seems to be extremely difficult to detect and, as expected, the situation is exacerbated as the mine is buried deeper. Past research efforts were conducted with two types of dipoles, a narrow band printed circuit dipole (PC dipole) used by the Cubic Corporation, and a relatively broadband brass dipole used by NBS. It was observed that the PC dipoles give good detection performance with mines buried in homogeneous, relatively dry soil. However, the response in moist or wet soil is known to degrade. Some evidence exists supporting the notion that the broadband dipole would perform much better under these conditions. Preliminary NBS research also

indicated that some frequencies penetrate moist soils much more efficiently than do others so that a "window of opportunity" may exist which can be used to enhance detection under wet conditions. These rumors and conjectures must be carefully investigated. Even if it turns out that the separated aperture approach simply does not work well in moist soil, this will still be important information regarding the generation of realistic specifications for a prototype vehicular and/or hand-held mine detector.

2 The operating bandwidth and frequency sampling interval must be optimized for best detection performance. The optimum choice for one set of conditions (e.g., dry soil) might not at all be optimum under other conditions (e.g., wet soil). Expansion at the lower end of the bandwidth could improve the performance in wet and heterogeneous soils. (Because of skin effect, low frequency energy generally penetrates lossy soil more effectively than does high frequency energy.[3]) NBS research indicated a greater confidence in 10 MHz interval bandwidth readings than with 20 MHz. Any "new start" program should carefully review the bandwidth/sampling interval issue.

Other deficiencies were outlined in Report 2412.[2] Throughout the history of the VMRMDS development, there was only one known correlation of simulated mines with those having high explosives (without fusing). In one test,[4] it was observed that 11 of 14 runs over an explosive-filled mine resulted in lower responses than "identical" runs over wax-filled mines. It was recommended that a greater in-depth study be initiated to correlate explosive-filled with inert-filled responses.

It was also noted that soil compaction by vehicle passage, especially tracked vehicles, invariably resulted in greater attenuation of the signal return. Naturally, the question arises, "Should a VMRMDS-like system be required to detect mines that have been run over several times prior to detonation?" (Remotely activated mines would not necessarily detonate on first pass.) It was recommended that this issue be examined when drafting future requirements documents.

According to Report 2412, the AN/VRS-5 signal display unit was, to say the least, not very "user friendly."

> "Interpretations of the pictures on the display is subjective and requires considerable practice and familiarization .... In the real battle scenario, the decision making by the operator would prove to be a fatiguing, traumatic experience .... A misinterpretation of an actual live mine detection could result in a terminal detonation." [2]

In summary, it is probably worthwhile to consider the final paragraph of the conclusions section of Report 2412:

> "This appraisal of the AN/VRS-5 development program is somewhat critical since it is relatively easy to find flaws in hindsight. It should be remember that the pressures of schedules, funding, and personnel perturbations do not appear in the overall picture but are a large part of program management. The development of this system demonstrates clearly that the technology offers considerable promise of detecting soil/mine anomalies under proper conditions but there are definite physical limitations which must be recognized. The system, itself, could even be developed to recognize and signal these limitations."[2]

PRESENT EFFORTS AND FUTURE PLANS

Because of the many attractive features of the separated aperture buried mine detection scheme, the Belvoir Countermine Technology Division has decided to initiate a new long term research program dedicated to the development of a complete understanding of the fundamental electromagnetic principles underlying this approach and to assess the general feasibility of separated aperture mine detectors.

At present, the authors of this report are conducting carefully controlled measurements at the Center's mine detection research facility. Results include measurements with both the printed circuit and broadband brass dipole antennas. To date, all experiments have been conducted in dry, loamy soil but experiments in moist and saturated soils are planned for the near future. The measurement setup and experimental results are described in detail below.

The National Institute of Standards and Technology (NIST) (formerly the National Bureau of Standards (NBS)) is under contract to the Center to provide guidance and assist Center personnel in the in-house measurement program mentioned above. They have been asked to generate a summary report of past NBS research efforts on the VMRMDS program. NIST will also provide the Center with a test fixture which can be used with the Center's Hewlett Packard 8753A RF Network Analyzer to measure the constitutive parameters (complex permittivity) of soils with varying moisture content.

The separated aperture sensor may respond to a rock or root in somewhat the same way it responds to a buried mine, resulting in an unacceptably high false alarm rate. At the present time Dr. Bernard Widrow and his graduate students at Stanford University, through support from the Center, are investigating the possibility of using a neural network with the separated aperture sensor to facilitate discrimination.[5] Neural networks, not unlike human beings, require "training" to become proficient at a task. In this case, the neural network requires a large amount of sensor data to "learn" the difference between a buried mine and background (no mine, but possibly other mine-like objects). Recently, a fairly extensive experimental data collection program has been completed. This data has been transferred to Stanford and will be used to train a neural network to discriminate between mines and other background anomalies (clutter) and between mine types.

SECTION II. EXPERIMENTAL RESULTS

DATA COLLECTION SYSTEM

Figure 3 (see Appendix A for all figures) shows a side view of the experimental data collection system which consists of a motorized three-wheeled cart, Hewlett Packard 8753 A network analyzer, Hewlett Packard Multi-programmer, and separated aperture sensor head. A front view of the system is shown in Figure 4. The height of the sensor head above the soil surface is adjusted using the hand crank and horizontal movement of the sensor is automatically controlled by a worm gear attached to a stepper motor. As shown in Figure 5, the test equipment is controlled by a Hewlett Packard 9000 model 236 desktop computer via a fiber optic link. Experimental data collected from the network analyzer is stored on a 3.5 inch floppy disk.

BROADBAND AND PRINTED CIRCUIT SENSOR HEADS

Figure 6 shows a close-up photograph of the 790 MHz sensor head which is composed of a transmit and receive broadband dipole pair separated by a metallic septum. Each broadband dipole resides within a corner reflector. The critical dimensions of the 790 MHz sensor head and broadband dipole are given in Figure 7. A few experiments were conducted using a broadband 1 GHz sensor and the critical dimensions for this head are shown in Figure 8. A 790 MHz sensor head using printed circuit dipoles is shown in Figure 9.

The bandwidth of the 790 MHz broadband and printed circuit sensor heads of Figures 6 and 9 is examined in Figure 10. Reflection coefficient (S11 dB) or standing wave ratio (SWR) is measured as a function of frequency for various heights of the sensor over dry, loamy soil. Figure 10a compares the reflection coefficient (S11 in dB) of the broadband and printed circuit dipoles for the frequency range from 300 kHz to 3 GHz when the sensors are 1 inch above the soil. Both dipoles are designed to resonate near 800 MHz and it is clear that the broadband dipole does indeed have greater bandwidth than the printed circuit dipole. An expanded view of this comparison is given in Figure 10d. Here, the SWR of the PC sensor is less than 3 from about .78 GHz to .82 GHz (a 40 MHz bandwidth), whereas the broadband sensor has an SWR less than 3 from about .75 GHz to .88 GHz (a 130 MHz bandwidth). In short, for this configuration, the broadband sensor returns less than 25% of the incident power to the source over a 130 MHz band; the PC sensor only performs that well over a 40 MHz band. Therefore, the broadband sensor has slightly more than three times the bandwidth of the PC sensor. Figures 10b and 10c demonstrate how the performance of the broadband and PC sensors vary for various sensor heights (1, 3, 5, and 7 inches).

EXPERIMENTAL PROCEDURE

This overview of the experimental test configuration defines the many variables which must be examined in order to develop a good understanding of the separated aperture dielectric anomaly detection scheme. Figure 11 is a scale drawing of the experimental configuration showing the 790 MHz broadband sensor parallel to and at a height H above the soil surface. A dielectric anomaly, usually a 12 x 12 x 3 inch nylon block, is buried at a depth D below the soil surface. For most of the experimental results presented here, the sensor head is scanned in 1.5-inch increments directly over the anomaly (receive dipole passes over the anomaly first). As shown in Figure 11, measurements are made at 27 positions for a total horizontal scan of 39 inches. At each horizontal position, the network analyzer is used to measure the transmission coefficient (S21), complex ratio of voltage at the output of the receive dipole to the voltage at the input of the transmit dipole, at 8 MHz intervals starting at 600 MHz and ending at 1,000 MHz—51 frequency samples over a 400 MHz band. Since the dipoles are resonant near 800 MHz, the transmission coefficient is measured from 200 MHz below resonance to 200 MHz above resonance. A 6-inch septum width was used for most of the data taken with the 790 MHz broadband sensor; however, the septum width can be adjusted.

Some measurements were made with the 790 MHz sensor head rotated 90 degrees so that the transmit and receive dipoles were parallel to the scan direction. Also, a few measurements were made with the 790 MHz PC dipole sensor and the 1 GHz broadband sensor. At one point, the resonant frequency of the 790 MHz sensor was lowered to 496 MHz by extending the length of the dipole arms via a metal sleeve. No other part of the sensor head was modified. As discussed in more detail later, results with this modified sensor were not very promising. Dielectric anomalies of styrofoam and water were also examined. The water was placed in a plastic garbage bag and then carefully lowered into a hole measuring 12 x 12 x 3 inches.

SOIL AND ANOMALY CONSTITUTIVE PARAMETERS

As one might expect, the ability to detect an anomaly buried in soil depends, among other things, on how different the electrical properties of the anomaly are from those of the background soil. It also depends on how much the soil attenuates electromagnetic energy. Electromagnetic energy, which must penetrate deep into lossy earth to interact with an anomaly, will be hopelessly lost in the noise by the time it reaches the receiver.

All the experimental results presented here were conducted in fairly dry, loamy soil with a moisture content of 6% by weight. The electrical properties of the soil were measured using a shielded open circuit coaxial line technique developed by researchers at the NIST.[6] The complex permittivity, $\hat{\varepsilon} = \varepsilon' - j\,\varepsilon'' = \varepsilon_0\,(\varepsilon_r' - j\,\varepsilon_r'')$ of the soil at 600 MHz, 790 MHz, and 1 GHz (the operating frequency range of the 790 MHz sensor) is $\varepsilon_0\,(2.8842 - j\,0.3712)$, $\varepsilon_0\,(2.8774 - j\,0.4443)$, and $\varepsilon_0\,(2.8806 - j\,0.5176)$, respectively, with $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m. It can easily be shown that a 790 MHz plane wave would be attenuated by 10 dB after propagating about 3.5 feet in this soil.[7]

As mentioned above, dielectric anomalies of styrofoam, nylon, and water were investigated. Styrofoam has electrical properties very similar to those of air; at 10 MHz, the permittivity of styrofoam is ε_0 (1.03 – j 0.0002). A nylon block with dimensions 12 x 12 x 3 inches was used in the majority of the experiments; at 100 MHz, nylon has a permittivity of ε_0 (3.16 – j 0.0660). A few experiments were performed using water as the anomaly; water has a dielectric constant at 300 MHz and 25°C of ε_0 (77.5 – j1.25). Permittivity data was taken from Harrington.[7] It is worth noting that styrofoam, nylon, and water have dielectric constants (real part of complex permittivity) less than, approximately equal to, and much greater than the loamy soil background.

COUPLING AS A FUNCTION OF SENSOR HEIGHT

Figure 12 plots the transmission coefficient for the 790 MHz broadband sensor as a function of frequency for various sensor heights. Proper operation of the separated aperture sensor requires that the direct signal coupled under the airspace between the septum and earth not mask the relatively weak signal from the buried dielectric anomaly. When the sensor is close to the earth, the septum and earth function like a waveguide that is below cutoff and thus the direct signal is significantly attenuated. From Figure 12, the coupling near resonance is suppressed by about 25 dB for heights of 1, 2, and 3 inches compared with coupling at a height of 6 inches. It will be shown later that this sensor head generally does not function properly for heights greater than about 4 inches.

SOIL HOMOGENEITY AND CONTROL OF SENSOR HEIGHT

Ideally, for a fixed sensor height, the transmission coefficient vs. frequency data should be independent of horizontal sensor position provided that the soil is homogeneous. Dirt clods and packing can create background soil inhomogeneities and the sensor height will be a function of position if the soil is not level. It is important to eliminate problems such as these so that any fluctuations in measured transmission coefficient can be solely attributed to the buried anomaly.

In an attempt to remedy these problems, the entire experimental test bed was overturned with a shovel down to a depth of about 2.5 feet, and the soil was vigorously chopped with a pickax to eliminate any dirt clods. Planks 4 x 4 inches in cross section were buried and leveled at 5-foot intervals across the test area. Using another plank, the soil between these parallel planks was leveled over the entire test area. A 4 x 8 foot sheet of 5/8 inch thick plywood was laid down over one end of the test bed so that the three-wheeled cart (see Figures 3 and 4) could move up and back on a stable platform without digging ruts into the soil. In short, these precautions were taken in order to ensure that the sensor height remained constant over every horizontal scan and that the background soil was as free from inhomogeneities as possible.

Figures 13 and 14 quantify the degree to which the soil can be viewed as a homogeneous background. Figure 13 provides plots of the transmission coefficient as a function of frequency for sensor heights of 1, 2, 3, 4, 5, and 6 inches at the far left (position 1), center (position 4), and far right (position 27) of a horizontal scan (see Figure 11). For sensor heights of 1 and 2 inches, the frequency responses at positions 1 and 14 are more or less the same (at least below 850 MHz), but the general shape of the response at position 27 seems to differ significantly from the response at positions 1 and 14, and at some frequencies by as much as 10 dB. At frequencies above 840 MHz, all three curves are somewhat different.

At sensor heights of 3 and 4 inches, the soil "looks" fairly homogeneous and at sensor heights of 5 and 6 inches, the soil "looks" perfectly homogeneous. It should be noted that as the sensor height increases, more and more energy is coupled directly through the airspace between the soil surface and septum. Thus, when the sensor height is large, the proportion of energy coupled through the soil is small compared with the direct coupled energy so that any soil inhomogeneities will be masked. (Compare the ordinate scale of Figures 13d, e, and f with those of Figures 13a, b, and c.)

Figure 14a and b provide a qualitative three-dimensional view of the soil background homogeneity as a function of frequency and position for sensor heights of 2 and 4 inches. Each figure is composed of 27 lines and each line corresponds to the transmission coefficient measured at the ith position along a horizontal scan. The first line in the foreground corresponds to the transmission coefficient measured at position 1 and the second line to measurements made at position 2, etc.

ABILITY OF 790 MHz SENSOR HEAD TO DETECT A BURIED NYLON BLOCK

Next, consider the ability of the broadband 790 MHz separated aperture sensor to detect a 12 x 12 x 3 inch nylon block buried at various depths in a background of relatively dry, loamy soil. Referring again to Figure 11, the transmission coefficient is measured at 27 positions in 1.5-inch increments across a horizontal scan for sensor heights of 1, 2, 3, 4, 5, and 6 inches, and nylon block depths of flush, 3, 6, 9, and 12 inches. (Note: The term *flush* indicates that the top of the nylon block is buried just under the surface of the soil, and a depth of 3 inches indicates that the top of the block is 3 inches below the soil surface, etc.) As previously mentioned, at each horizontal position, the transmission coefficient is measured at 51 discrete frequencies from 600 MHz to 1,000 MHz. The sensor dipoles are resonant near 790 MHz, and the sensor is scanned directly over the anomaly in such a way that the receive dipole passes over the anomaly first.

Transmission coefficient measurements will be a function of frequency, position, sensor height, and anomaly depth. In Figure 15, the anomaly is buried flush with the surface; in Figure 16, the anomaly is buried 3 inches deep, and so forth for Figures 17 and 18; and in Figure 19, the surface of the anomaly is 12 inches below the soil-air interface. Each figure has six plots corresponding to sensor heights of 1, 2, 3, 4, 5, and 6 inches. Each plot gives transmission coefficient (S21) vs. frequency data at sensor positions 1 (to the far left of the anomaly), 14 (directly over the anomaly), and 27 (to the far right of the anomaly).

Figures 20 through 25 display exactly the same information as Figures 15 through 19 except in a different format. In Figures 20 through 25, the sensor height is the constant parameter rather than anomaly depth. In Figure 20, the sensor height is 2 inches above the soil; in Figure 21, the sensor is

3 inches above the soil; etc. Each figure has five plots corresponding to anomaly depths of flush, 3, 6, 9, and 12 inches. Each plot gives transmission coefficient (S21) vs. frequency data at sensor positions 1, 14, and 27.

Several observations can be made from the above data. When the sensor height is less than about 4 inches, the response (S21) at position 14 is generally greater than when the sensor is at position 1 or 27. This statement is generally true over the entire frequency range from 600 MHz to 1,000 MHz; in fact, at some frequencies (Figure 15a), the difference in anomaly and background response can be as large as 25 dB.

Recall that when the sensor is close to the soil surface and over homogeneous background, the waveguide formed between the septum and soil interface is below cutoff so that direct coupling between transmit and receive dipoles is small. When the sensor is close to the earth and directly over the anomaly, the anomaly provides an additional propagation path and consequently coupling between transmit and receive dipoles increases.

When the sensor height is greater than about 4 inches, it is no longer generally true that the response at position 14 is greater than at position 1 or 27. For example (from Figure 15f), for frequencies below about 820 MHz, the response at position 14 is less than the background response, and above 840 MHz the opposite is true.

At sensor heights greater than 4 inches, the waveguide formed between the septum and soil interface is no longer below cutoff and considerable direct coupling takes place. When the sensor is directly over the anomaly, coupling through the anomaly can either constructively or destructively interfere (add in or out of phase) with the direct coupling so that the net response can either be greater or less than the background response.

The difference between the response (S21) at position 14—sensor over anomaly—and position 1 or 27—sensor away from the anomaly (the *difference response*)—generally decreases as the sensor height and/or anomaly depth increases. This result is expected and is merely a statement that for a given sensor height, the deeper the anomaly the harder it is to "see," and for a given depth, the anomaly becomes harder to "see" as the sensor height increases. From Figure 20, when the sensor is only 2 inches from the soil surface, the maximum difference response is at least 15 dB even when the anomaly is buried 12 inches below the surface. On the other hand, from Figure 23, when the sensor height is 4 inches above the soil, the difference response is small for anomaly depths greater than 3 inches. In short, acceptable performance can be expected for anomaly depths up to 6 inches provided the sensor height does not exceed 3 inches. This conclusion is valid only over the range of experimental conditions considered. Under different conditions (e.g., sensor design, anomaly size, soil type and moisture content, etc.) the result might be quite different. Moist or wet soil conditions, all other parameters held constant, might considerably reduce the range of anomaly depths and sensor heights over which acceptable performance could be expected.

SENSOR RESPONSE AS A FUNCTION OF POSITION

Another meaningful way to present the data obtained from the experiment depicted in Figure 11 is to plot the transmission coefficient as a function of position for fixed frequency. In Figure 26, the response vs. position of the broadband sensor at 796 MHz (the resonant frequency of the sensor dipoles) is given for sensor heights of 1, 3, 4, and 6 inches and anomaly (12 x 12 x 3 inch nylon block) depths of flush, 3, 6, 9, and 12 inches.

For sensor heights less than 4 inches and anomaly depths up to 6 inches, Figure 26 clearly shows that there is peak in the response when the sensor is directly over the anomaly. It is also interesting to note that there is often, but not always, a dip in the response curve on either side of the peak. This phenomenon is particularly pronounced for the case when the anomaly is buried just under the soil surface (flush) and the sensor is at a height of 4 inches (see Figure 26a). In this case, the dip to the left/right of the peak occurs when the leading edge of the septum just passes over the left/right edge of the anomaly.

As expected, as the anomaly depth or sensor height increases beyond 4 and 6 inches, respectively, the peak in the response becomes washed out. The peak for an anomaly depth of 9 inches and a sensor height of 4 inches (see Figure 26d) is actually below the background level. In this case, however, the dips associated with the septum passing over the edges of the anomaly still mark its position.

Figure 27 provides plots of S21 vs. position for various sensor heights and anomaly depths similar to the results provided in Figure 26, except that sensor has been rotated 90 degrees with respect to the direction of scan. Conclusions drawn regarding Figure 26 also apply to Figure 27. The dips in the response curve again occur just as the septum passes over the edge of the anomaly. Notice that rotating the sensor has broadened the response of Figure 27a relative to that of Figure 26a. As expected, this relative broadening is less pronounced as the anomaly depth or sensor height increases. Compare Figures 26e and 27c.

Figure 28 compares the response of the 1 GHz broadband sensor, 790 MHz broadband sensor, and a sensor formed by adding metallic sleeves to the dipoles of the 790 MHz sensor so that they resonate near 500 MHz. (Note that only the length of the dipole arms were increased in developing the "500 MHz sensor"; no other part of the 790 MHz septum or corner reflector geometry was modified.) The response of the 790 MHz sensor is clearly superior to either of the other two sensors. However, for a smaller anomaly, it is quite possible that the 1 GHz sensor would provide the best performance. One problem with the 1 GHz sensor is that its response degrades rather rapidly with height in comparison with the 796 MHz sensor. The response of the 1 GHz sensor is nearly flat at a height of 4 inches and is completely washed out at 5 inches. On the other hand, the 790 MHz sensor "sees" the anomaly very well at a height of 4 inches and "sees" the anomaly somewhat even at a height of 5 and 6 inches. The performance of the 500 MHz sensor leaves much to be desired. It was originally conjectured that the height sensitivity could be improved by lowering the resonant frequency of the 790 MHz sensor to 500 MHz. This may be true, but the test results are inconclusive since the septum and reflector geometries were not also scaled. The fact that the 6-inch septum is electrically 62.5% shorter at 500 MHz than at 790 MHz leads one to conclude that it is very likely that there is too much direct coupling from transmit to receive dipole. It may also turn out that the resolution of the senor at 500 MHz, even if properly scaled, would be less than desirable.

Figure 29 compares the response of the broadband 790 MHz sensor with that of the 790 MHz printed circuit (PC) sensor. Since both sensors are operated at very near their resonant frequencies (790 MHz), there is very little difference in their overall performance. Because the bandwidth of the broadband dipoles is significantly greater than the PC dipoles (see Figure 10) the broadband sensor may well perform better in a detection algorithm that utilizes a wider band of frequencies. Furthermore, under stringent conditions (e.g., anomalies buried deep in moist or wet soil), one would expect bandwidth to play an even more significant role in the detection process.

Figure 30 compares the response of 12 x 12 x 3 inch anomalies of styrofoam, nylon, and water buried just under the surface of dry, loamy soil. As previously mentioned, the water anomaly was created by filling a thin plastic garbage bag with the proper amount of water so as to just fill a hole of dimensions 12 x 12 x 3 inches. It is interesting to note that the largest response occurred for the styrofoam anomaly. In fact, styrofoam gave a fairly substantial response (relative to background) even at a sensor height of 6 inches. The response when the sensor was directly over water was always greater than when the sensor was over background. For heights of 5 and 6 inches, the response when the sensor was directly over nylon was less then when the sensor was over background.

SECTION III. SUMMARY

This report provided an overview of research efforts, both past and present, with the waveguide beyond cutoff or separated aperture dielectric anomaly detection scheme. Most significantly, it was stated that this sensor exhibits the best signal-to-clutter ratio of any electromagnetic detection technique ever attempted. It was pointed out that the improved signal-to-clutter ratio is obtained when the sensor is close to the ground and consequently this detection technique is most applicable to relatively level, sparsely vegetated terrain.

Previous research efforts with the separated aperture approach, which eventually led to a Vehicle-Mounted Road Mine Detector System (VMRMDS), AN/VRS-5,[2] were reviewed and it was pointed out that the AN/VRS-5 eventually failed because of its inability to detect mines buried deep in moist or wet soil. Other less serious deficiencies were discussed and it was concluded that the AN/VRS-5 efforts clearly demonstrated that the separated aperture technology offers considerable promise of detecting soil/mine anomalies under proper conditions, but there are definite physical limitations which must be recognized. It was pointed out that an increased operating bandwidth and frequency sampling interval might well improve the detection performance of the sensor, especially in wet soils. Furthermore, the printed circuit dipoles used in the AN/VRS-5 were inherently narrow band in comparison with the broadband brass dipoles used in the NIST research. Therefore, it was concluded that it is probably wise to use broadband brass dipoles in any further prototypes.

Present efforts and future plans were outlined. Additional experiments will be conducted at the Center's mine detection research facility by personnel in the Countermine Technology Division. Data recently collected at the Center has been transferred to Stanford University. Stanford plans to use this data to train a neural network to discriminate between mines and other background anomalies, clutter, and between mine types. The NIST has been asked to generate a summary report of past NIST research efforts on the VMRMDS program and to provide the Center with a test fixture which can be used with the Center's Hewlett Packard 8735-A Network Analyzer to measure the constitutive parameters of soils with varying moisture content.

OBSERVATIONS

In Section II of this report, the data collection system housed at the Center's mine detection research facility was described. The following important observations were made regarding the experimental data presented in this report:

1. The broadband sensor has roughly three times the bandwidth of the printed circuit (PC) sensor (see Figure 10).

2. Coupling from transmit to receive dipole is a relatively sensitive function of sensor height. Coupling near resonance (790 MHz) is suppressed by about 25 dB for sensor heights of 1, 2, and 3 inches compared with coupling at a height of 6 inches (see Figure 12).

3. In spite of efforts to eliminate dirt clods and soil packing, soil inhomogeneities were still apparent when the sensor was close (within 3 inches) to the earth. However, the return from a buried anomaly (a 12 x 12 x 3 inch nylon block buried less than 6 inches deep) is large compared with fluctuations in the return due to soil inhomogeneities.

4. A considerable amount of data was presented (see Figures 15 through 25) which characterized the ability of the 790 MHz sensor to detect a 12 x 12 x 3 inch nylon block buried in a background of relatively dry, loamy soil. Transmission coefficient data was presented as a function of frequency for sensor heights of 1, 2, 3, 4, 5, and 6 inches and nylon block depths of flush, 3, 6, 9, and 12 inches. **Acceptable performance (the anomaly was "visible") can be expected for anomaly depths up to 6 inches provided the sensor height does not exceed 3 inches.**

5. The sensor response as function of position at the resonant frequency of the sensor showed (see Figure 26) that there is a peak in the response when the sensor is directly over the anomaly and that there is a dip or null on either side of the peak. The dip to the left/right of the peak occurs when the leading edge of the septum just passes over the left/right edge of the buried anomaly. As the anomaly depth or sensor height increases beyond 6 and 4 inches, respectively, the peak in the response becomes washed out.

6. Rotating the sensor with respect to the direction of scan (see Figure 27) does not appreciably change the response.

7. The 790 MHz sensor performed better than either the 1 GHz or 500 MHz sensors (see Figure 28). For small anomalies, the 1 GHz sensor may perform best. The 500 MHz sensor may have performed better if the entire 790 MHz sensor was scaled—not just the dipoles.

8. As demonstrated in Figure 29, the broadband sensor performed about as well as the PC sensor. Over a broader range of frequencies, the broadband sensor would probably perform better than the PC sensor.

9. Figure 30 compares the response of 12 x 12 x 3 inch anomalies of styrofoam, nylon, and water buried just under the surface of dry, loamy soil. The largest response (relative to background) was obtained from the styrofoam anomaly.

RECOMMENDATIONS FOR FURTHER RESEARCH

The experimental data discussed in this report represents, at best, only a first order effort at completely characterizing the performance of the separated aperture dielectric anomaly detection scheme. Additional experiments will be required in order to gain a more complete comprehension of the operating characteristics and inherent limitations of this sensor.

As previously mentioned, the most serious problem with the AN/VRS-5 was its extremely poor detection rate of mines buried in high-moisture content soils. It was also conjectured that the broadband sensor would perform better than the PC sensor in moist or wet soils. Therefore, it is recommended that experiments conducted with the 12 x 12 x 3 inch nylon block be repeated in moist soils with both the broadband and PC sensor heads.

Most of the experimental data presented in this report dealt with the ability of the 790 MHz broadband sensor to detect a 12 x 12 x 3 inch nylon block buried in a background of dry, loamy soil. The 12 x 12 x 3 inch anomaly is about the same size as an antivehicular mine. Antipersonnel mines are typically smaller than antivehicular mines so that additional experimental data with a smaller anomaly and the 1 GHz sensor head would be required to optimize sensor design for detection of antipersonnel mines.

A considerable amount of experimental data was generated by NIST on the old VMRMDS program and, as previously mentioned, NIST is presently generating a written summary of these efforts. With this document in hand, it will be much easier to make an accurate assessment of the present state of the experimental database and to identify areas requiring further experimental efforts. Also, a substantially expanded experimental effort may be warranted depending on the relative success of the Stanford neural network research.

It is not difficult to see that an enormous experimental effort is required to completely characterize sensor performance. Unfortunately, even a thorough measurement program will not necessarily provide an adequate understanding of the fundamental mechanisms which control the detection process. Experimental techniques provide the "answer" but they do not necessarily provide a *reason* for the "answer." Therefore, it is recommended that a theoretical analysis be initiated with the goal of providing a complete understanding of the fundamental electromagnetic principles underlying the separated aperture mine detection technique.

In summary, a carefully orchestrated theoretical and experimental effort will probably provide the best possible opportunity to select optimum design specifications for a close-in mine detection prototype based on the separated aperture detection technique.

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APPENDIX A
ILLUSTRATIONS

Figure	Title	Page

Figure	Title	Page

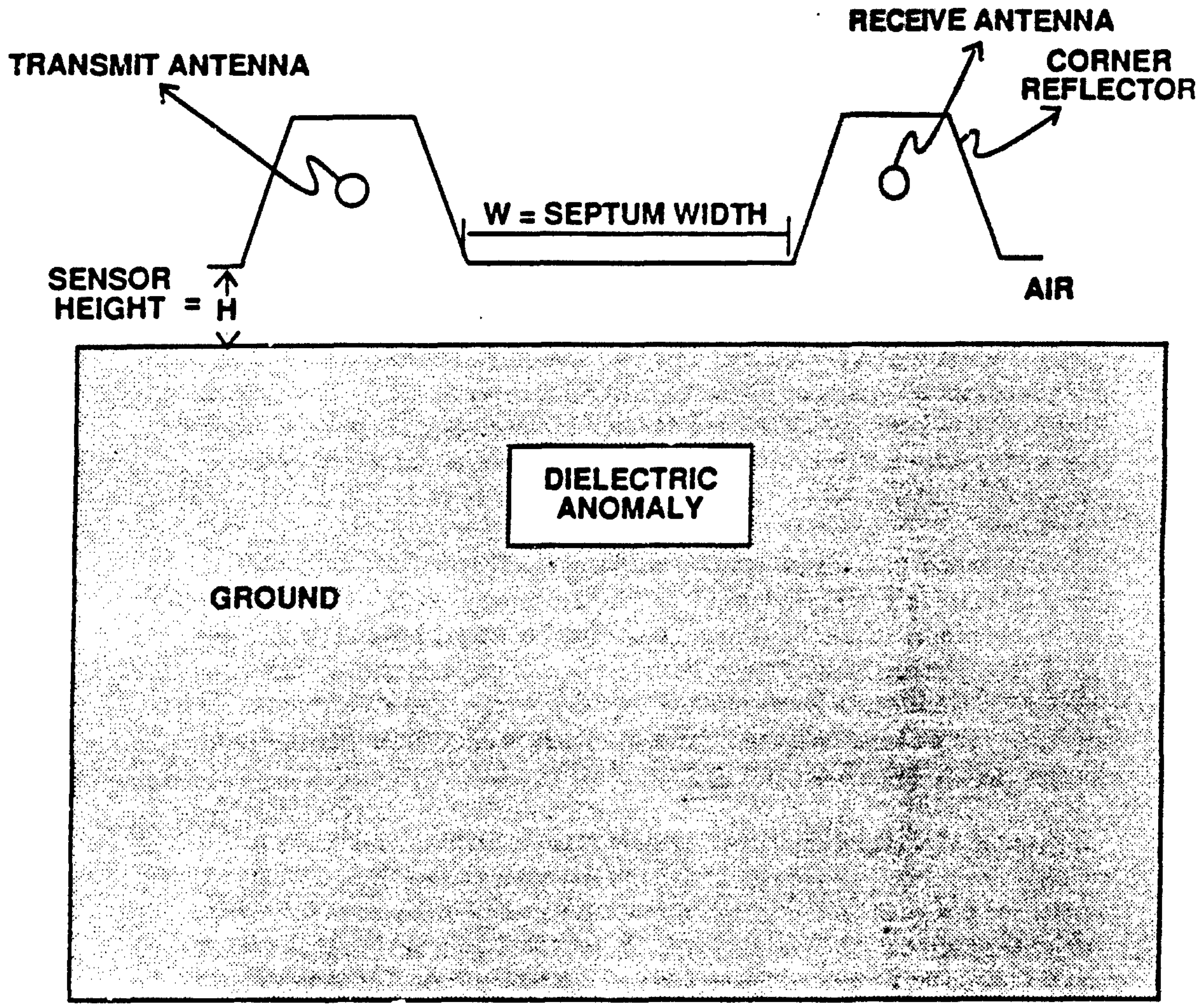


Figure 1. Simple schematic of the separated aperture or waveguide beyond cutoff mine detection system. When the sensor is over homogeneous earth (no mine present), very little power is received. There is a significant increase in received power when the sensor is over a mine. Best mine detection performance requires careful optimization of sensor parameters (i.e., sensor height, septum width, etc.)

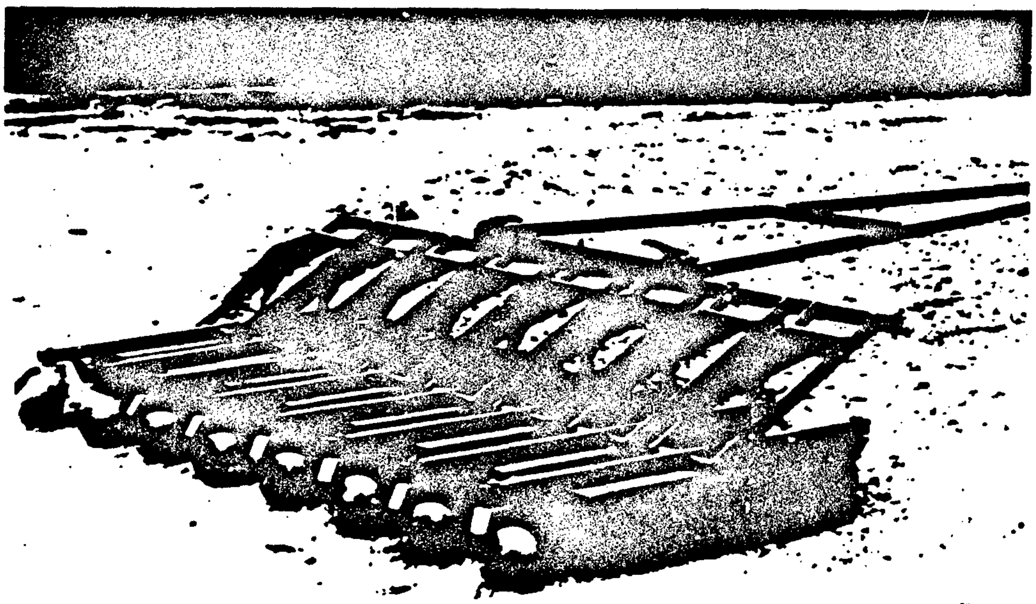


Figure 2. Close-in front view of AN/VRS-5 detector

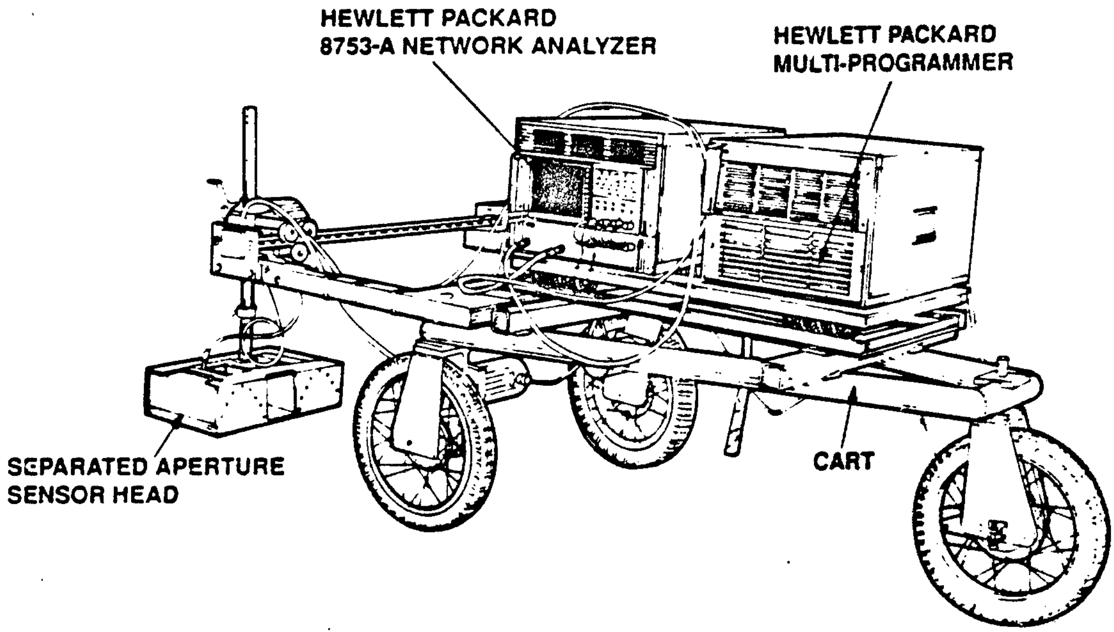


Figure 3. Side view of experimental setup consisting of motorized three-wheeled cart, Hewlett Packard 8753-A network analyzer and multi-programmer, and separated aperture sensor head

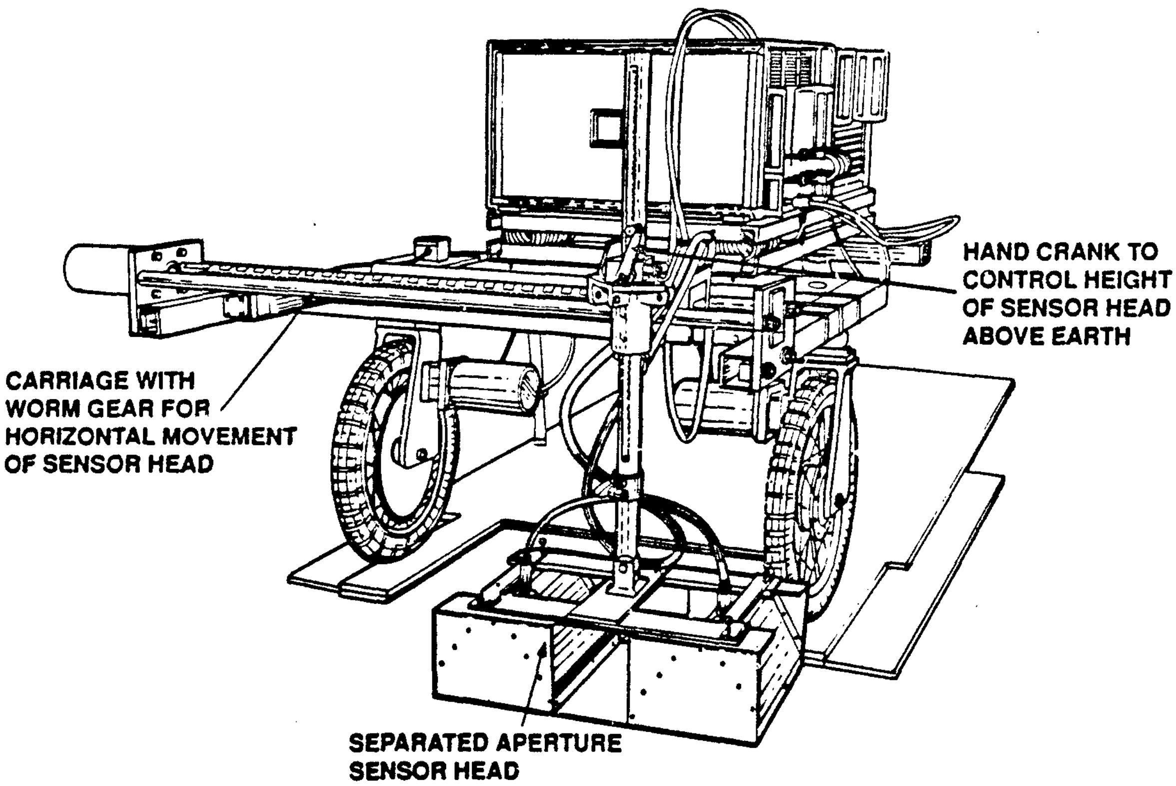


Figure 4. Front view of experimental test setup showing sensor head, hand crank to control height of sensor head above earth, and carriage with worm gear for horizontal movement of sensor head

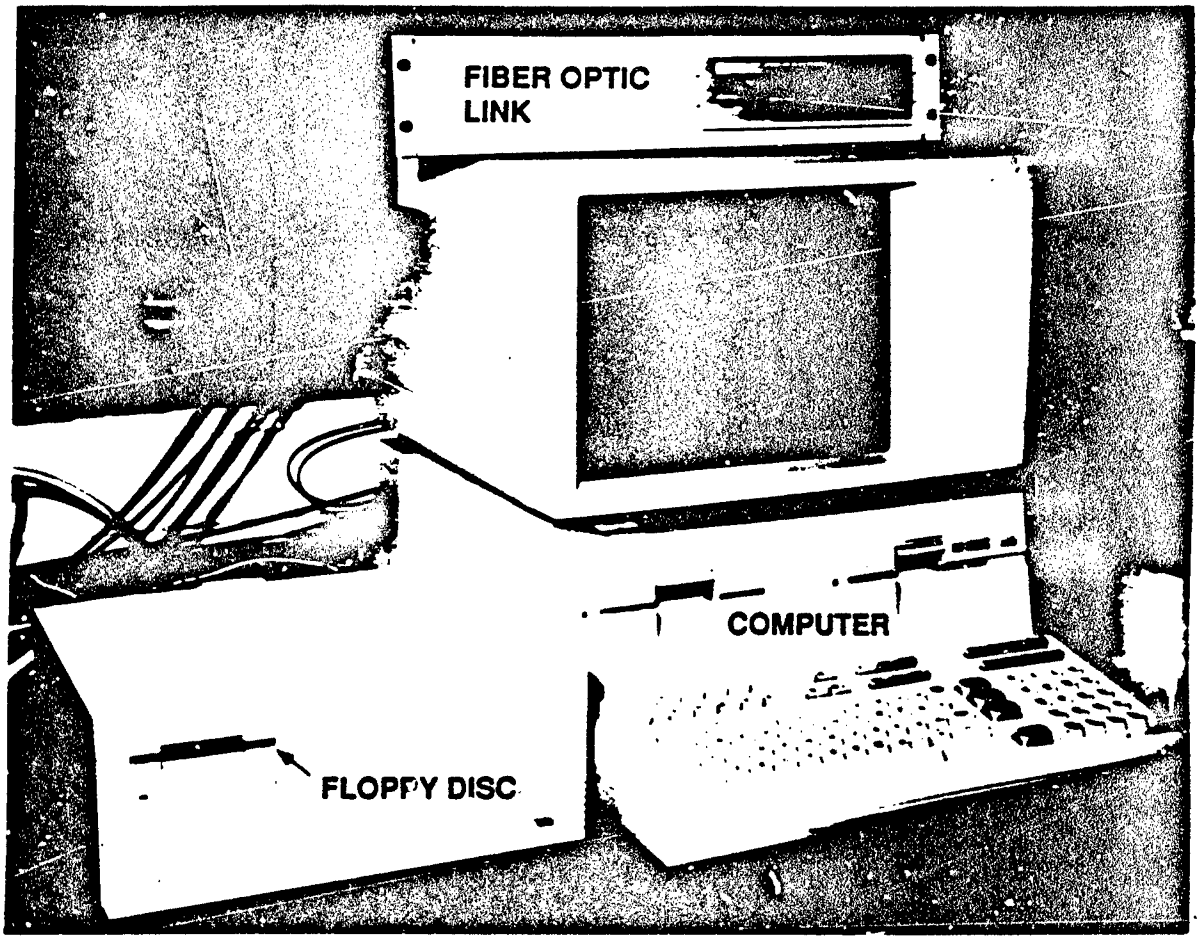


Figure 5. Hewlett Packard 9000 Model 236 desktop computer used to control, via a fiber optic link, the experimental test setup of Figures 3 and 4. Experimental data collected from the network analyzer is stored on a $3^1/_2$ inch floppy disc

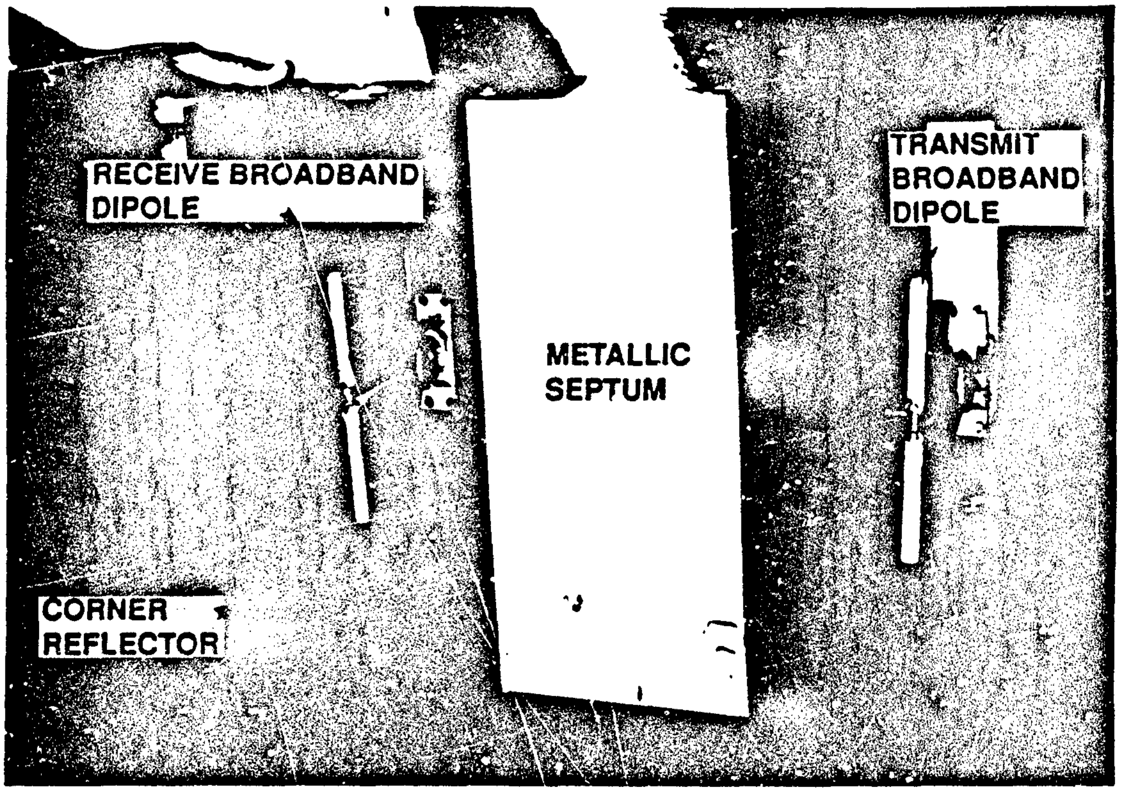


Figure 6. Close up photograph of 790 MHz sensor head, composed of a transmit and receive broadband dipole pair, separated by a metallic septum; each broadband dipole resides within a corner reflector

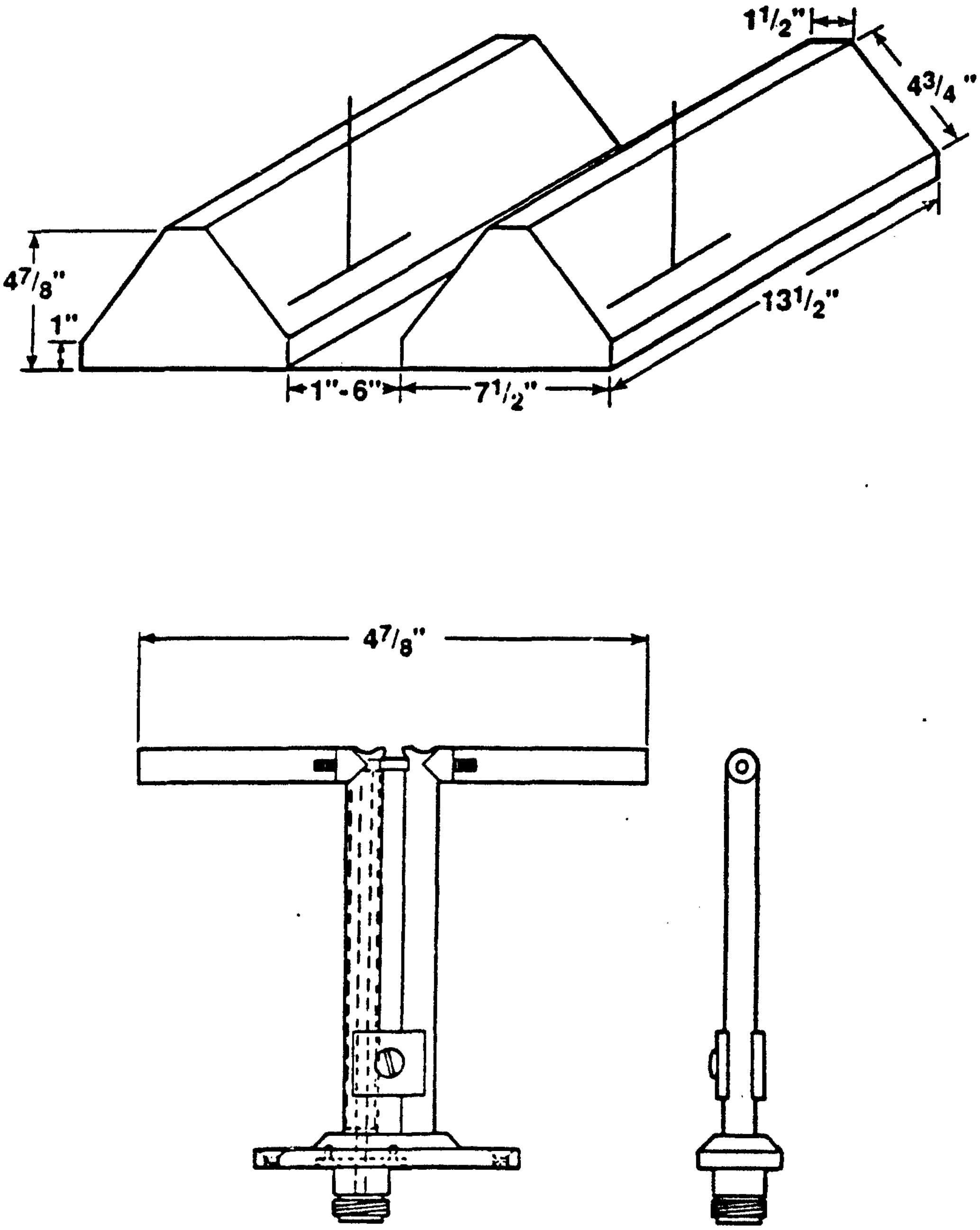


Figure 7. Critical dimensions of 790 MHz sensor head and 790 MHz broadband dipole

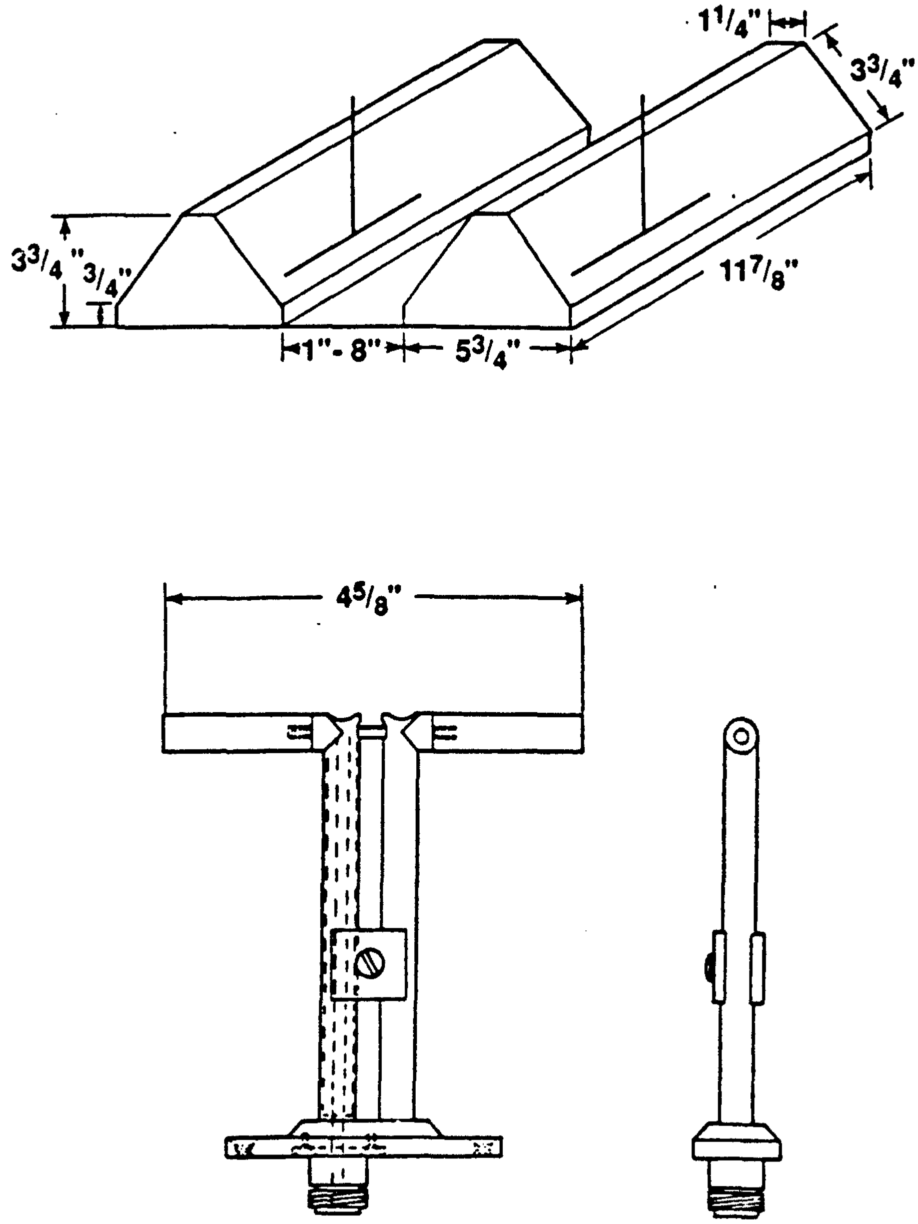


Figure 8. Critical dimensions of 1 GHz sensor head and 1 GHz broadband dipole

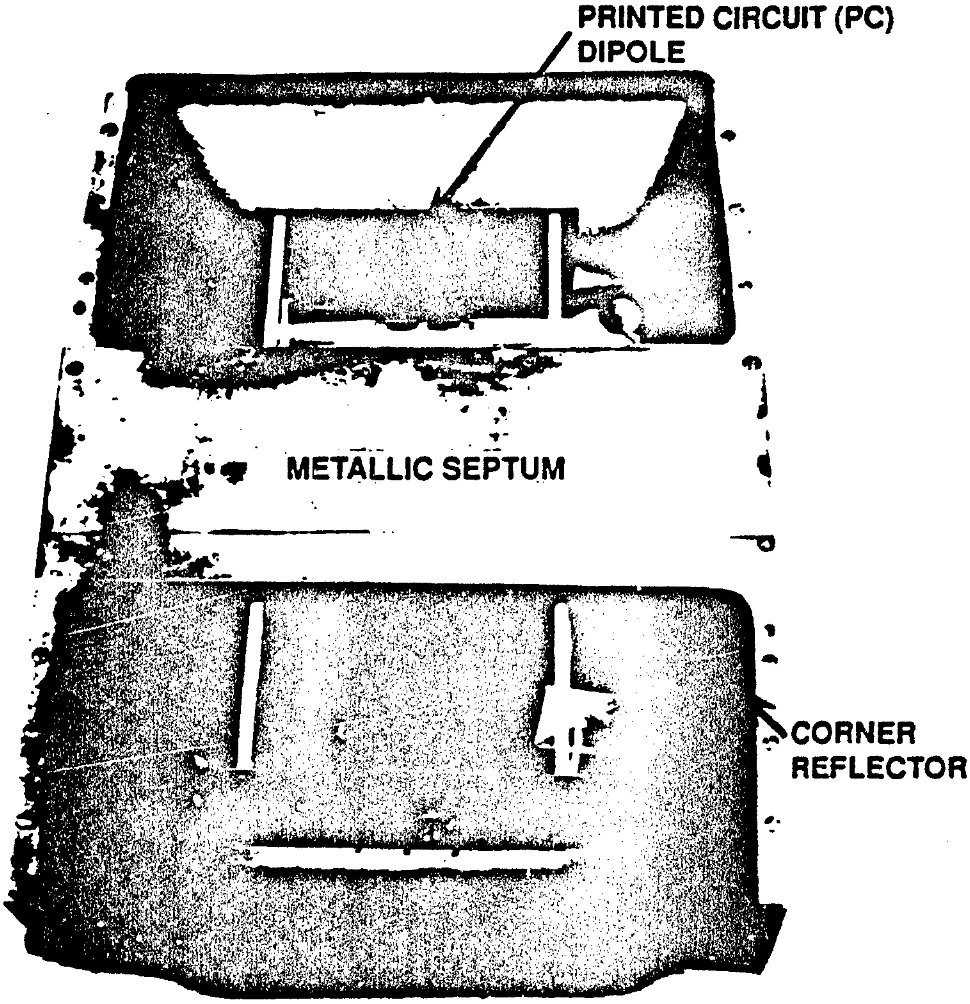


Figure 9. Close-up photograph of 790 MHz head, composed of a transmit and receive printed circuit (PC) dipole pair, separated by a metallic septum; each PC dipole resides within a corner reflector

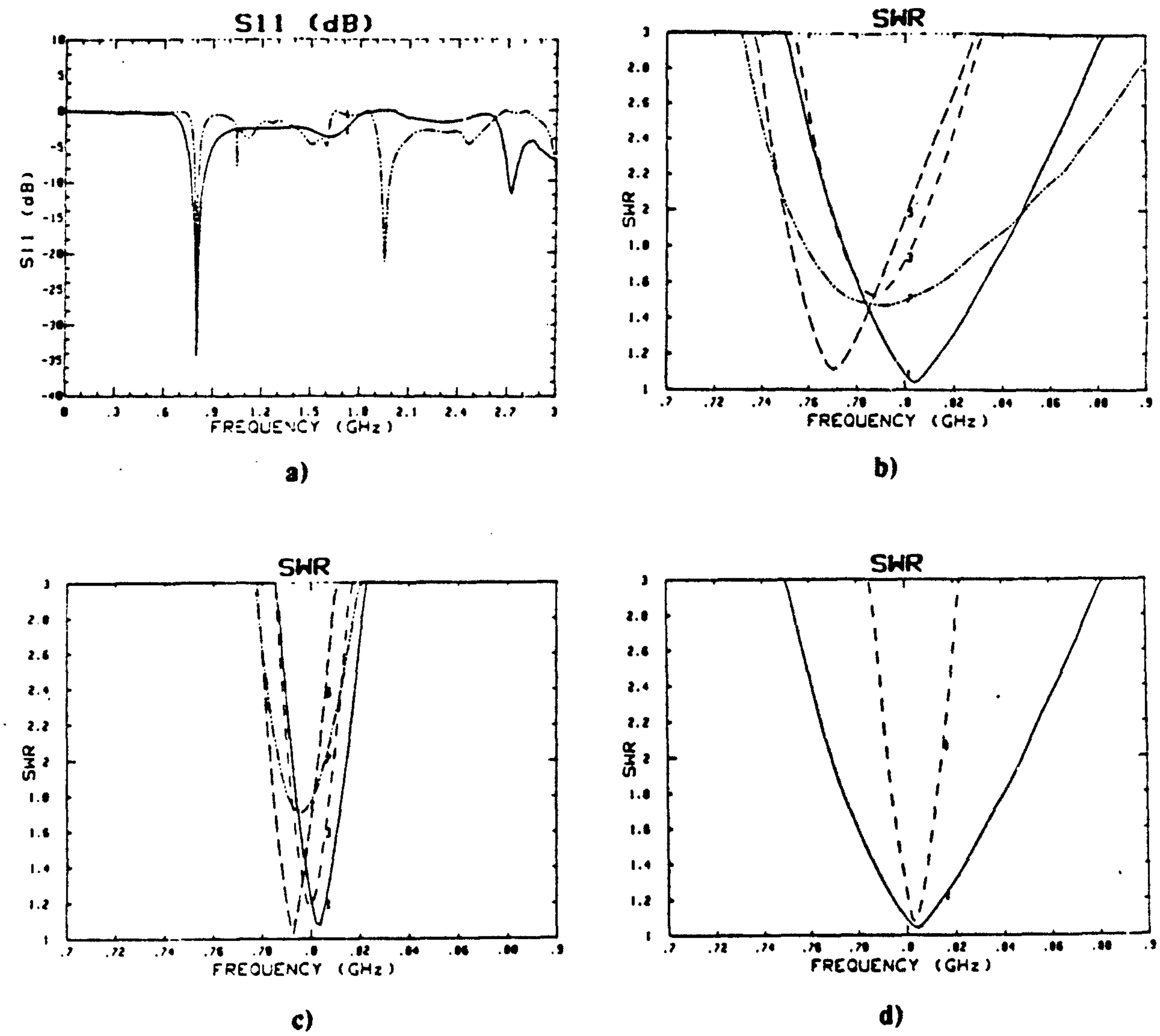


Figure 10. Reflection coefficient (S11 dB) or standing wave ratio (SWR) as a function of frequency for broadband and printed circuit (PC) dipoles. Measurements were made with the dipoles in the sensor head (see Figures 6 and 9) with the sensor head at various heights above the earth (dry, loamy soil):

a) broadband dipole (——), PC dipole (- — -) for a 1 inch sensor height
b) broadband dipole for sensor heights of 1, 3, 5, and 7 inches
c) PC dipole for sensor heights of 1, 3, 5, and 7 inches
d) broadband dipole (——), PC dipole (——) for a sensor height of 1 inch

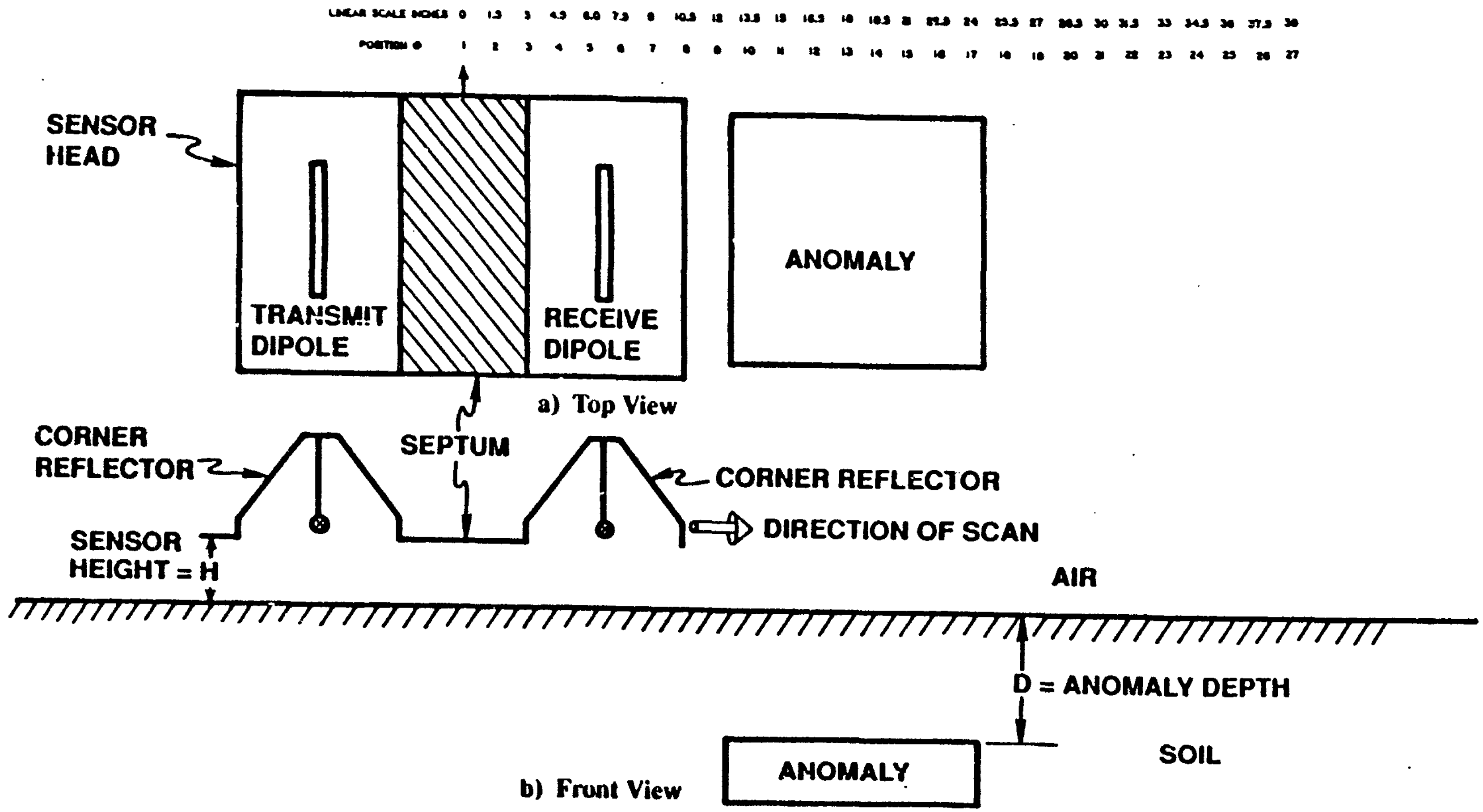


Figure 11. Scale drawing of experimental configuration showing 790 MHz sensor head (see Figure 6) parallel to and at a height **H** above the soil surface and dielectric anomaly (12 x 12 x 3 inches) buried at depth **D** below the soil surface. The sensor head is scanned directly over the anomaly in the direction shown (receive dipole passes over the anomaly first) in 1.5-inch increments for a total horizontal scan of 39 inches. The broadband dipoles are resonant at 790 MHz (see Figure 10). The sensor head septum width is adjustable in 1-inch increments over a range from 1 to 6 inches; however, for most of the data shown here, the septum width is held fixed at 6 inches

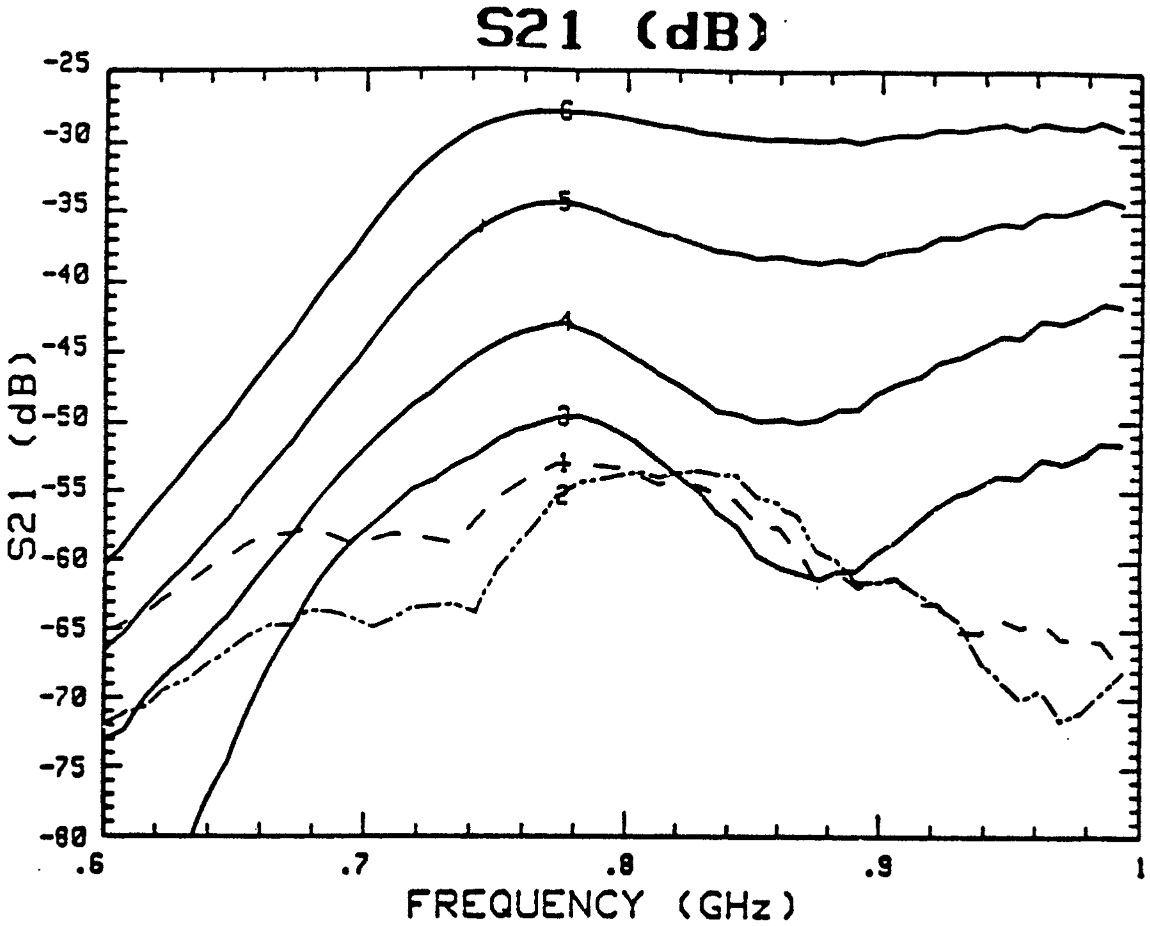
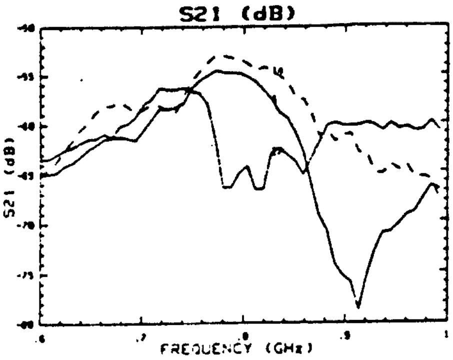
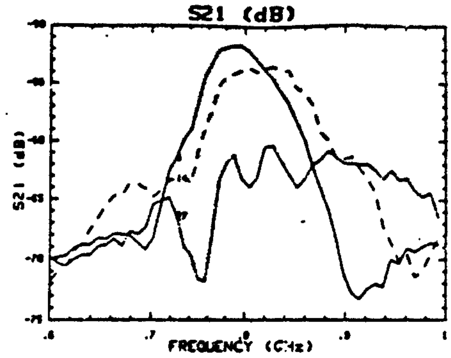


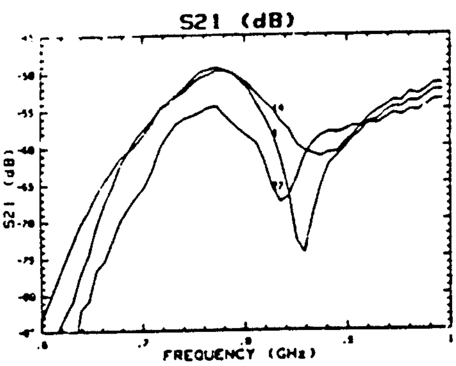
Figure 12. Measurement of transmission coefficient (S21) as a function of frequency over dry, loamy soil for broadband sensor heights of 1, 2, 3, 4, 5, and 6 inches; no dielectric anomaly present



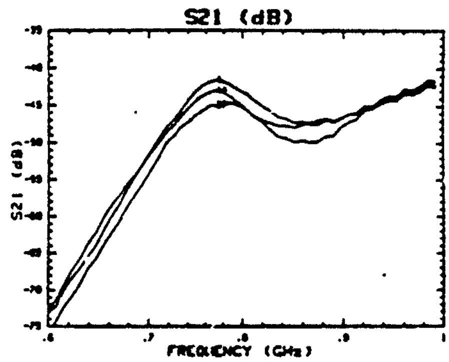
a) Sensor Height = 1 inch



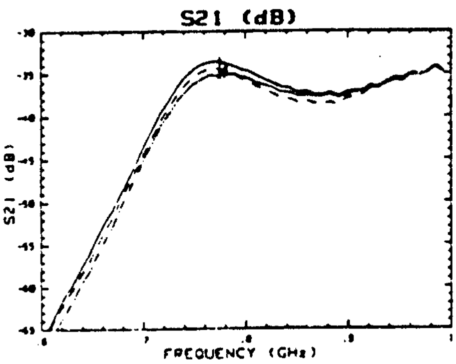
b) Sensor Height = 2 inches



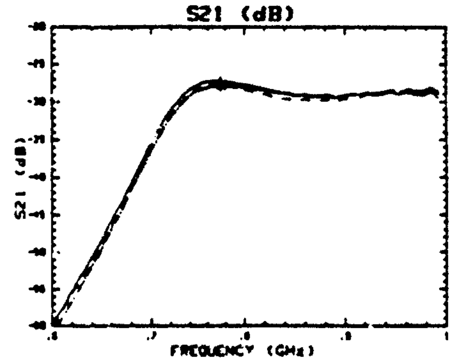
c) Sensor Height = 3 inches



d) Sensor Height = 4 inches

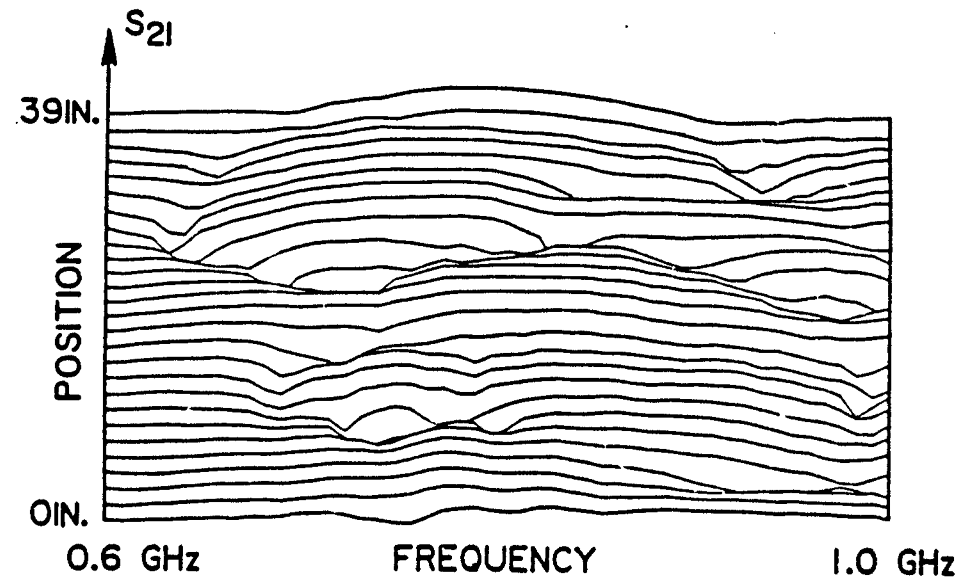


e) Sensor Height = 5 inches

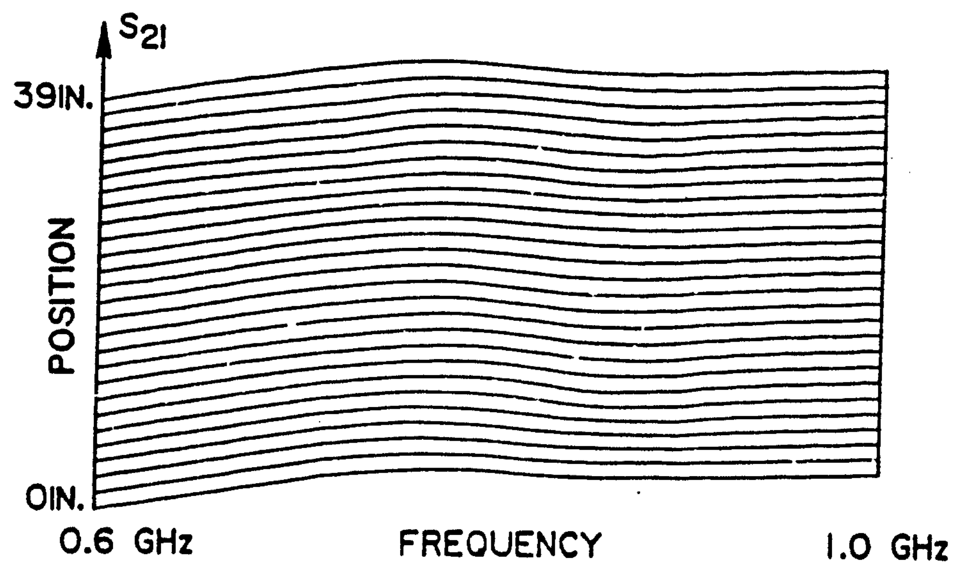


f) Sensor Height = 6 inches

Figure 13. Measurement of transmission coefficient (S21) as a function of frequency over dry, loamy soil with no dielectric anomaly present. In each figure curves 1, 14, and 27 correspond, respectively, to the sensor head at the far left, center and far right of a 39-inch horizontal scan. The broadband sensor is: a) 1 inch; b) 2 inches; c) 3 inches; d) 4 inches; e) 5 inches; f) 6 inches above the soil

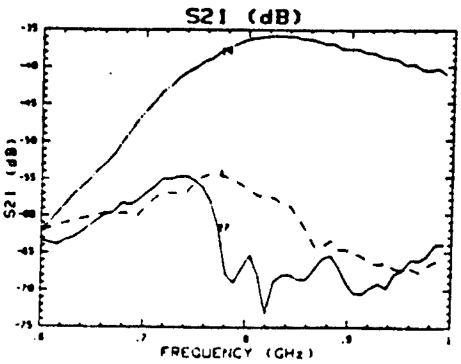


a) Sensor Height = 2 inches

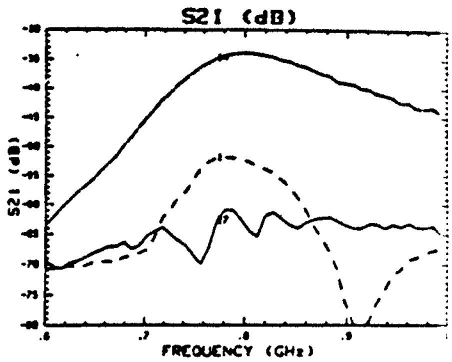


b) Sensor Height = 4 inches

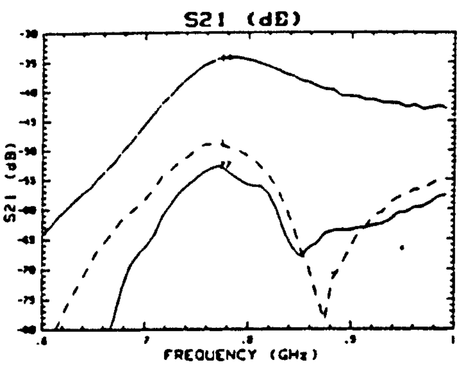
Figure 14. Measurement of transmission coefficient (S21) as a function of frequency and sensor position. The broadband sensor is scanned over dry, loamy soil at a height of: **a)** 2 inches; **b)** 4 inches



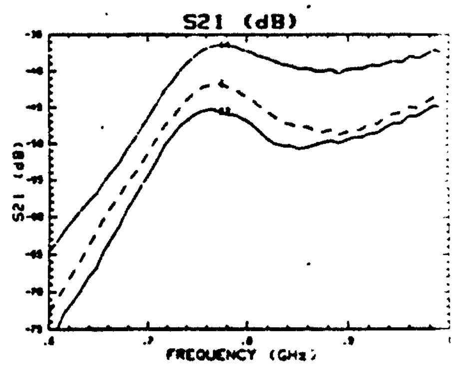
a) Sensor Height = 1 inch



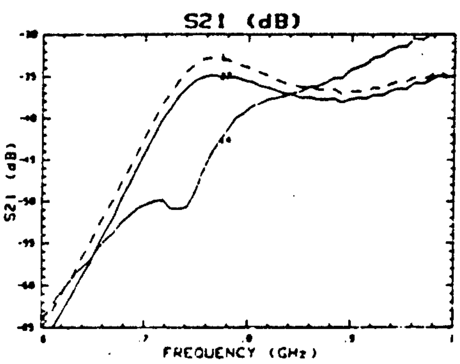
b) Sensor Height = 2 inches



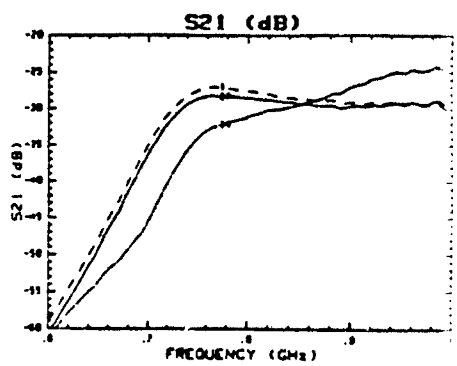
c) Sensor Height = 3 inches



d) Sensor Height = 4 inches

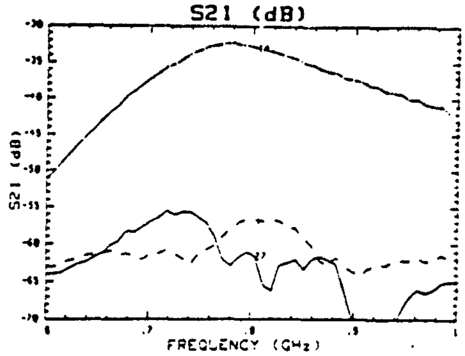


e) Sensor Height = 5 inches

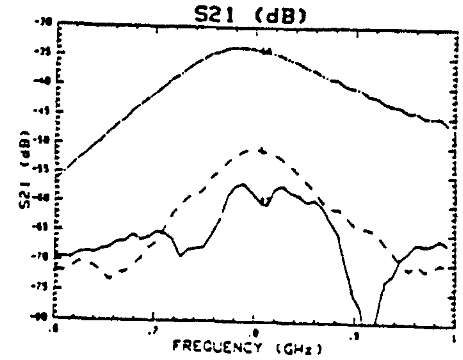


f) Sensor Height = 6 inches

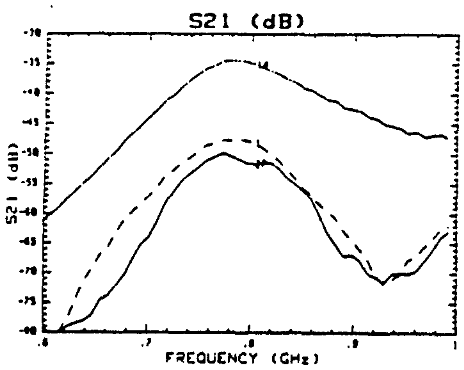
Figure 15. Measurement of transmission coefficient (S21) as a function of frequency over dry, loamy soil. In each figure, curves 1, 14, and 27 correspond, respectively, to the sensor head at the far left, center, and far right of a 39-inch horizontal scan. A nylon block (12 x 12 x 3 inches) is buried **flush with the surface** so that the broadband sensor head is centered directly over the nylon block at position 14. The broadband sensor is: **a)** 1 inch; **b)** 2 inches; **c)** 3 inches; **d)** 4 inches; **e)** 5 inches; **f)** 6 inches above the soil



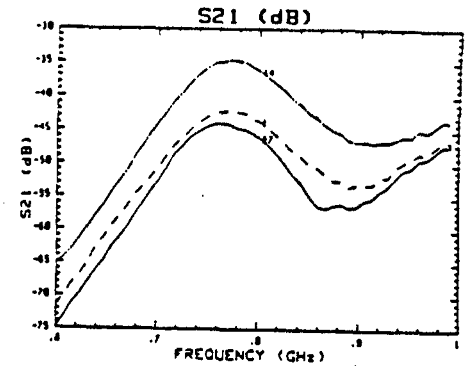
a) **Sensor Height = 1 inch**



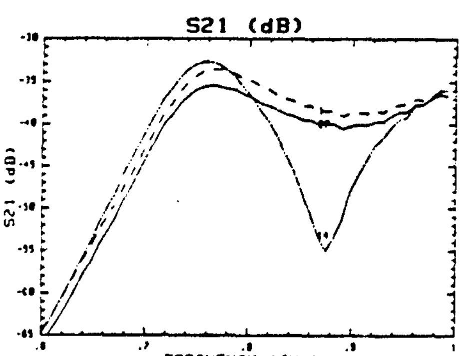
b) **Sensor Height = 2 inches**



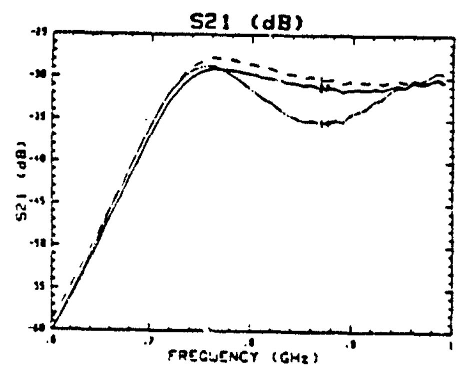
c) **Sensor Height = 3 inches**



d) **Sensor Height = 4 inches**

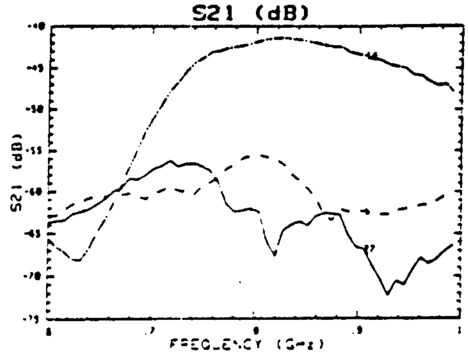


e) **Sensor Height = 5 inches**

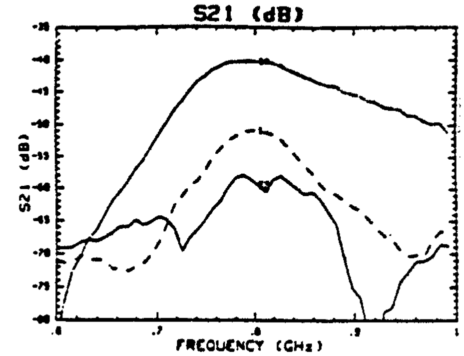


f) **Sensor Height = 6 inches**

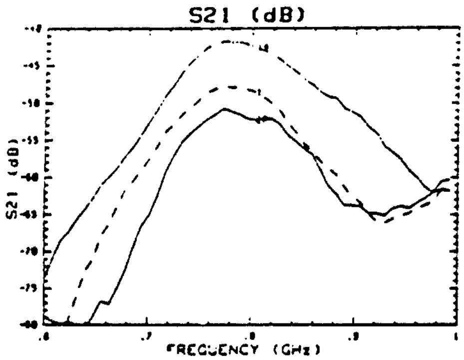
Figure 16. Measurement of transmission coefficient (S21) as a function of frequency over dry, loamy soil In each figure, curves 1, 14, and 27 correspond, respectively, to the sensor head at the far left, center, and far right of a 39-inch horizontal scan. A nylon block (12 x 12 x 3 inches) is buried **3 inches below** the soil surface so that the broadband sensor head is centered directly over the nylon block at position 14. The broadband sensor is: **a)** 1 inch; **b)** 2 inches; **c)** 3 inches; **d)** 4 inches; **e)** 5 inches; **f)** 6 inches above the soil



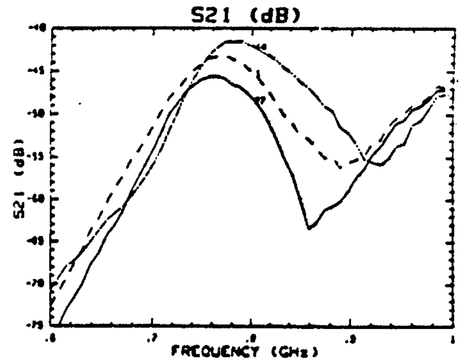
a) **Sensor Height = 1 inch**



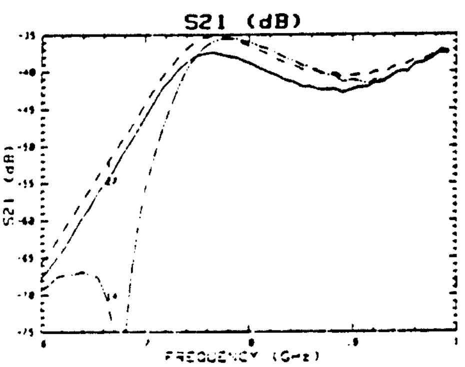
b) **Sensor Height = 2 inches**



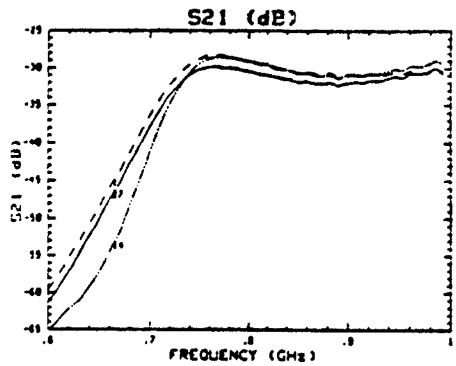
c) **Sensor Height = 3 inches**



d) **Sensor Height = 4 inches**

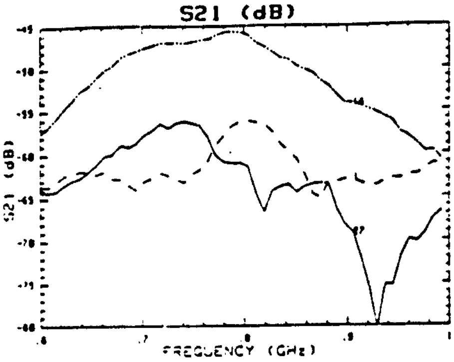


e) **Sensor Height = 5 inches**

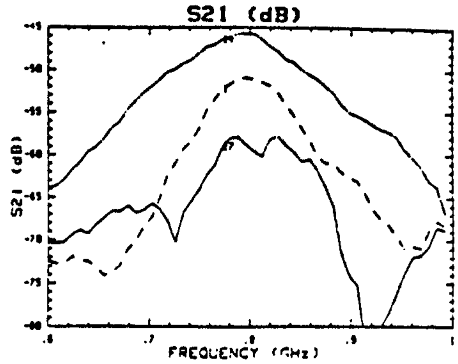


f) **Sensor Height = 6 inches**

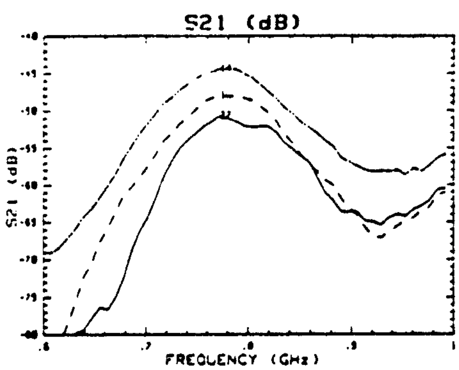
Figure 17. Measurement of transmission coefficient (S21) as a function of frequency over dry, loamy soil. In each figure, curves 1, 14, and 27 correspond, respectively, to the sensor head at the far left, center, and far right of a 39-inch horizontal scan. A nylon block (12 x 12 x 3 inches) is buried **6 inches below** the soil surface so that the broadband sensor head is centered directly over the nylon block at position 14. The broadband sensor is: **a)** 1 inch; **b)** 2 inches; **c)** 3 inches; **d)** 4 inches; **e)** 5 inches; **f)** 6 inches above the soil



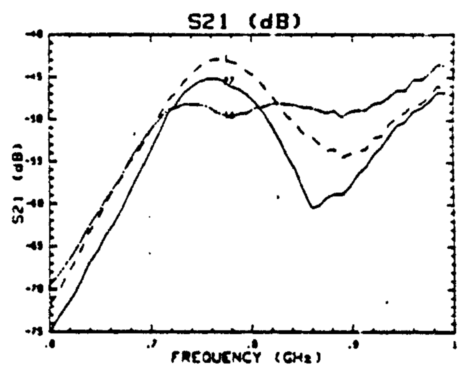
a) **Sensor Height = 1 inch**



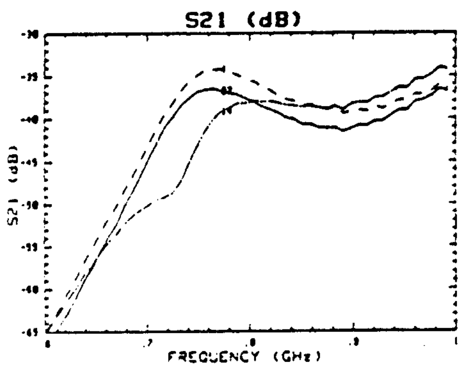
b) **Sensor Height = 2 inches**



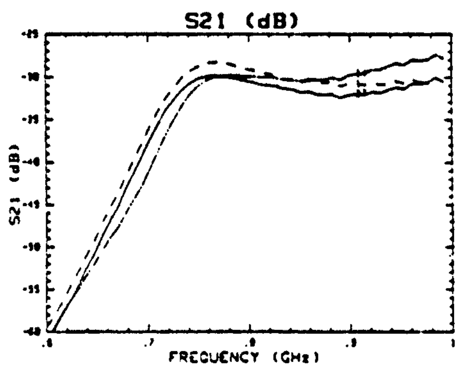
c) **Sensor Height = 3 inches**



d) **Sensor Height = 4 inches**

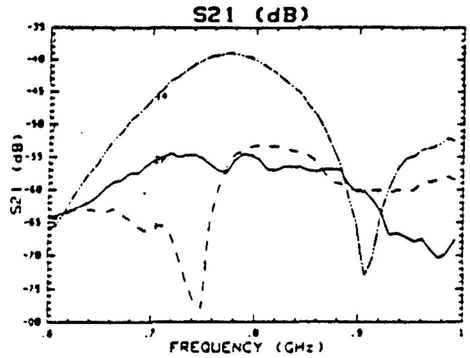


e) **Sensor Height = 5 inches**

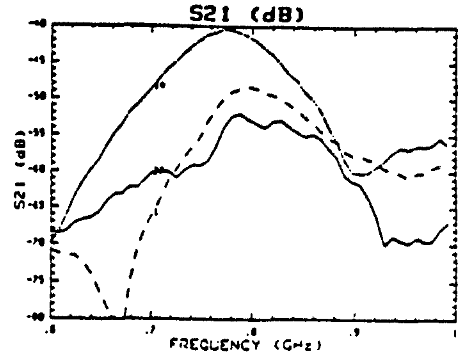


f) **Sensor Height = 6 inches**

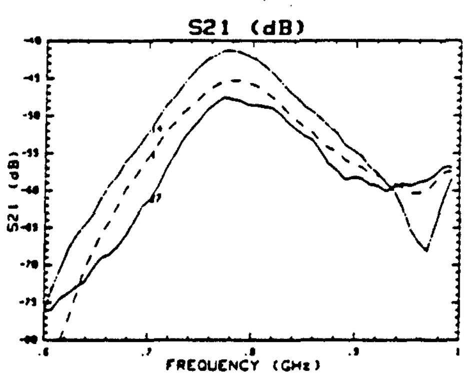
Figure 18. Measurement of transmission coefficient (S21) as a function of frequency over dry, loamy soil. In each figure, curves 1, 14, and 27 correspond, respectively, to the sensor head at the far left, center, and far right of a 39-inch horizontal scan. A nylon block (12 x 12 x 3 inches) is buried 9 inches below the soil surface so that the broadband sensor head is centered directly over the nylon block at position 14. The broadband sensor is: **a)** 1 inch; **b)** 2 inches; **c)** 3 inches; **d)** 4 inches; **e)** 5 inches; **f)** 6 inches above the soil



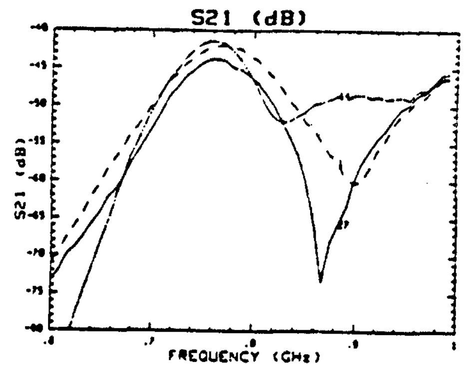
a) Sensor Height = 1 inch



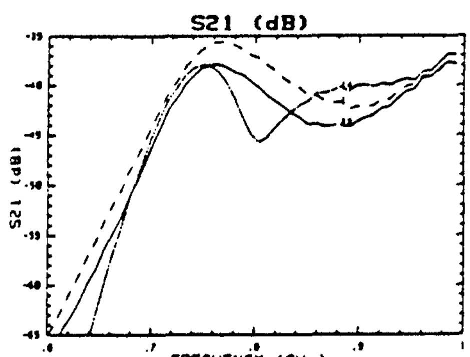
b) Sensor Height = 2 inches



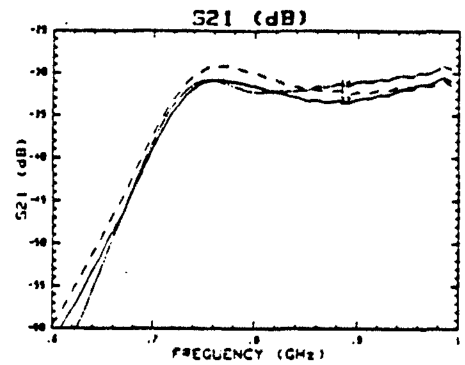
c) Sensor Height = 3 inches



d) Sensor Height = 4 inches

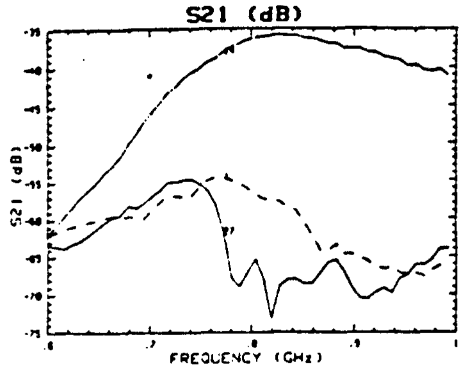


e) Sensor Height = 5 inches

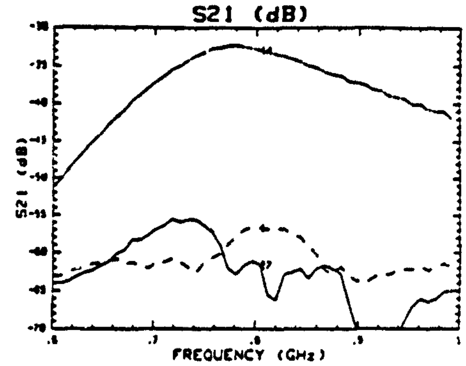


f) Sensor Height = 6 inches

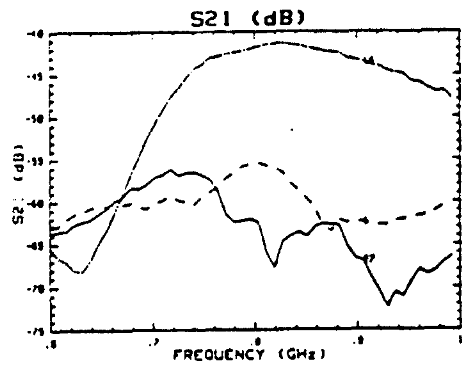
Figure 19. Measurement of transmission coefficient (S21) as a function of frequency over dry, loamy soil. In each figure, curves 1, 14, and 27 correspond, respectively, to the sensor head at the far left, center, and far right of a 39-inch horizontal scan. A nylon block (12 x 12 x 3 inches) is buried **12 inches below** the soil surface so that the broadband sensor head is centered directly over the nylon block at position 14. The broadband sensor is: **a)** 1 inch; **b)** 2 inches; **c)** 3 inches; **d)** 4 inches; **e)** 5 inches; **f)** 6 inches above the soil



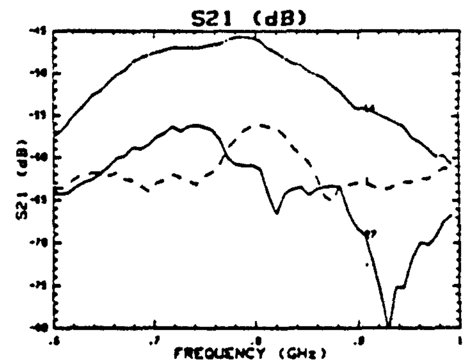
a) Anomaly Depth = Flush



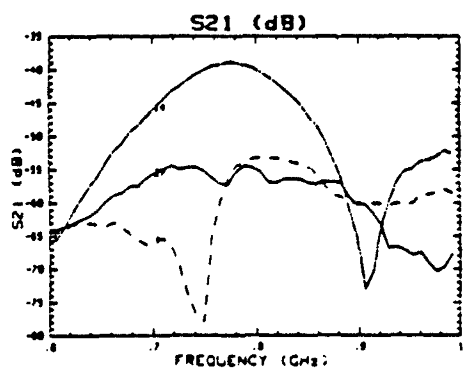
b) Anomaly Depth = 3 inches



c) Anomaly Depth = 6 inches

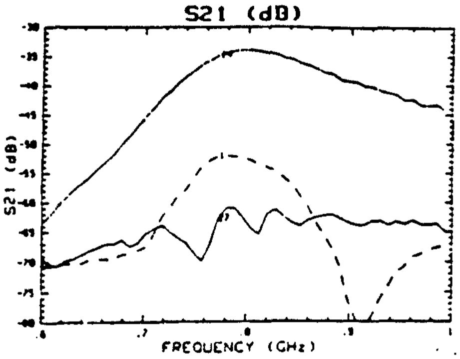


d) Anomaly Depth = 9 inches

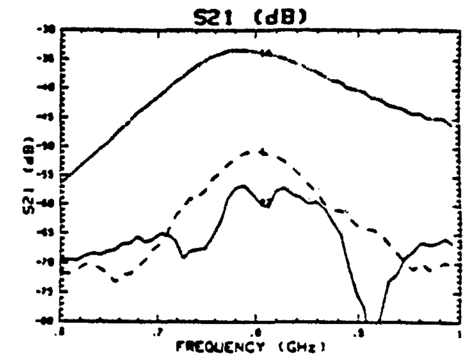


e) Anomaly Depth = 12 inches

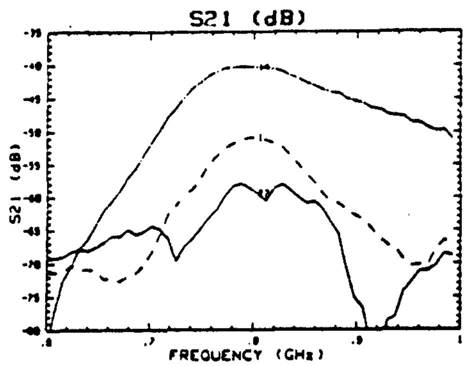
Figure 20. Measurement of transmission coefficient (S21) as a function of frequency over dry, loamy soil. In each figure, curves 1, 14, and 27 correspond, respectively, to the sensor head at the far left, center, and far right of a 39-inch horizontal scan. The broadband sensor is 1 inch above the soil. A nylon block (12 x 12 x 3 inches) is buried: **a)** flush; **b)** 3 inches; **c)** 6 inches; **d)** 9 inches; **e)** 12 inches with/below the soil surface so that the broadband sensor is centered directly over the nylon block at position 14



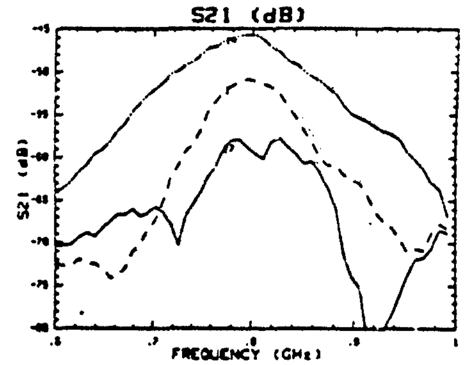
a) **Anomaly Depth = Flush**



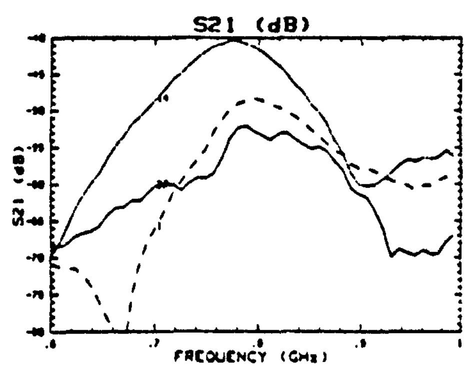
b) **Anomaly Depth = 3 inches**



c) **Anomaly Depth = 6 inches**

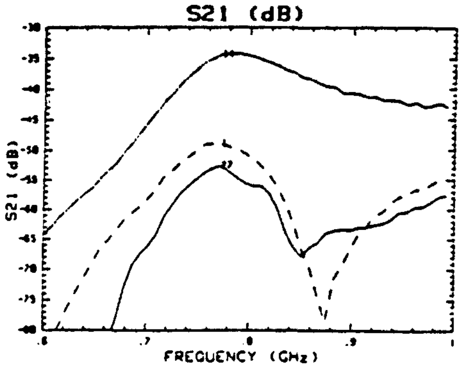


d) **Anomaly Depth = 9 inches**

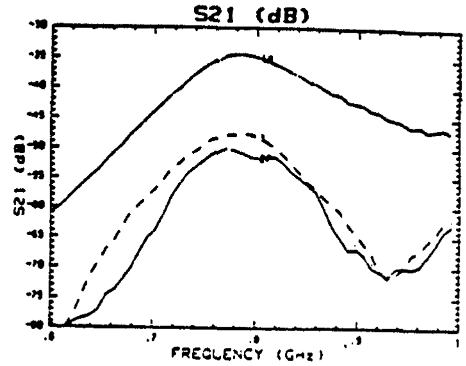


e) **Anomaly Depth = 12 inches**

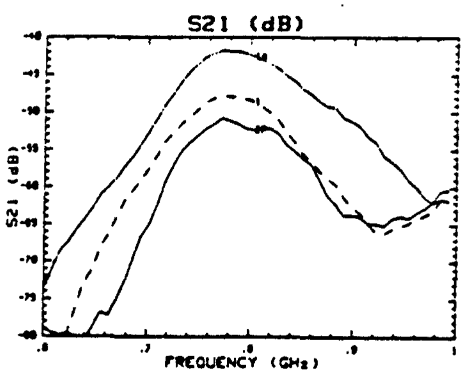
Figure 21. Measurement of transmission coefficient (S21) as a function of frequency over dry, loamy soil. In each figure, curves 1, 14, and 27 correspond, respectively to the sensor head at the far left, center, and far right of a 39-inch horizontal scan. The broadband sensor is **2 inches above** the soil. A nylon block (12 x 12 x 3 inches) is buried: **a)** flush; **b)** 3 inches; **c)** 6 inches; **d)** 9 inches; **e)** 12 inches with/below the soil surface so that the broadband sensor is centered directly over the nylon block at position 14



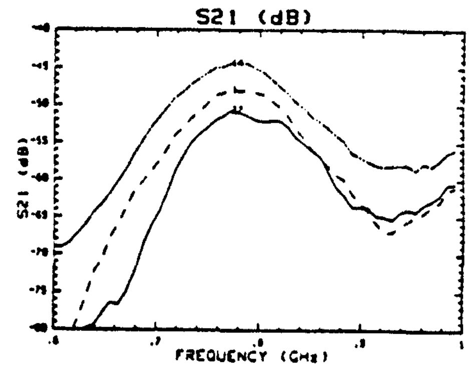
a) Anomaly Depth = Flush



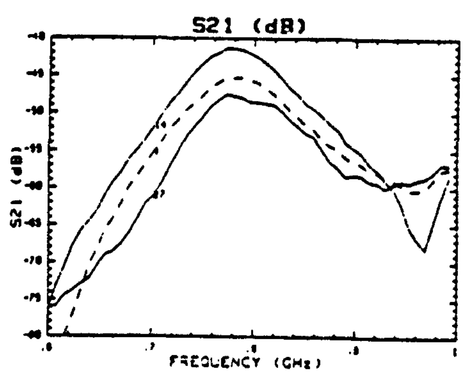
b) Anomaly Depth = 3 inches



c) Anomaly Depth = 6 inches

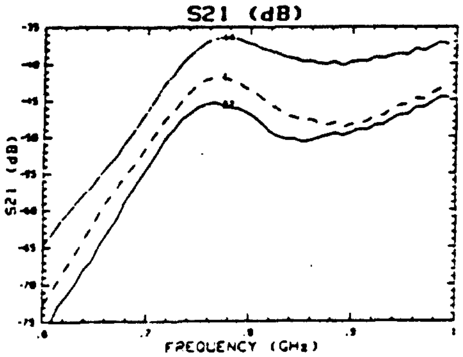


d) Anomaly Depth = 9 inches

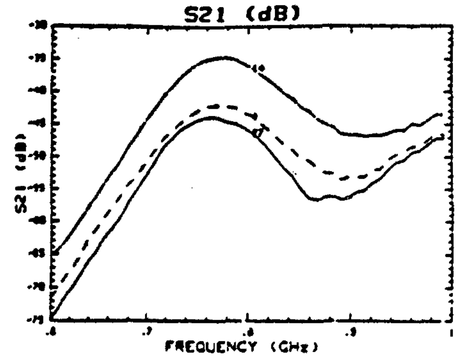


e) Anomaly Depth = 12 inches

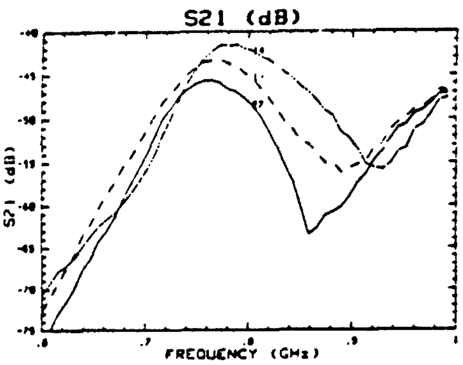
Figure 22. Measurement of transmission coefficient (S21) as a function of frequency over dry, loamy soil. In each figure, curves 1, 14, and 27 correspond, respectively, to the sensor head at the far left, center, and far right of a 39-inch horizontal scan. The broadband sensor is **3 inches above** the soil. A nylon block (12 x 12 x 3 inches) is buried: **a)** flush; **b)** 3 inches; **c)** 6 inches; **d)** 9 inches; **e)** 12 inches with/below the soil surface so that the broadband sensor is centered directly over the nylon block at position 14



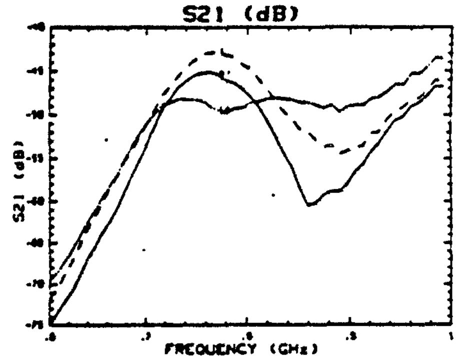
a) **Anomaly Depth = Flush**



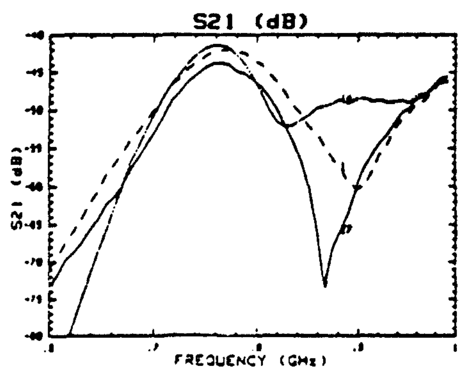
b) **Anomaly Depth = 3 inches**



c) **Anomaly Depth = 6 inches**

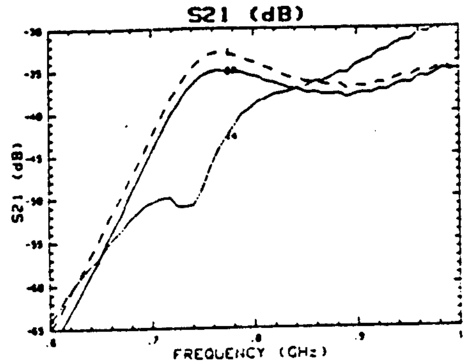


d) **Anomaly Depth = 9 inches**

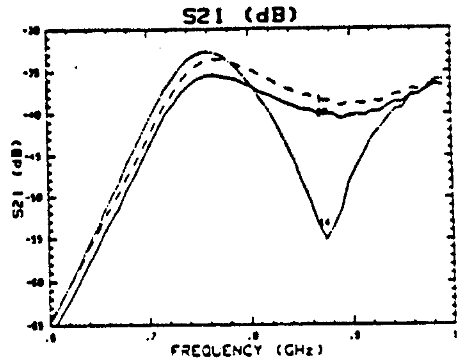


e) **Anomaly Depth = 12 inches**

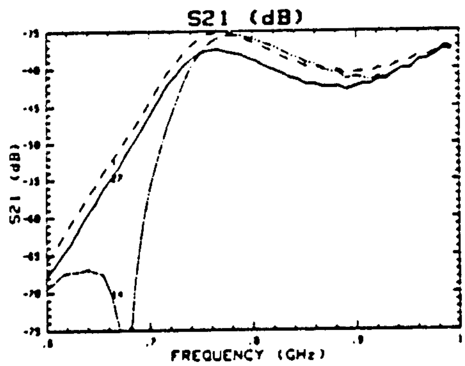
Figure 23. Measurement of transmission coefficient (S21) as a function of frequency over dry, loamy soil. In each figure, curves 1, 14, and 27 correspond, respectively, to the sensor head at the far left, center, and far right of a 39-inch horizontal scan. The broadband sensor is 4 inches above the soil. A nylon block (12 x 12 x 3 inches) is buried: **a)** flush; **b)** 3 inches; **c)** 6 inches; **d)** 9 inches; **e)** 12 inches with/below the soil surface so that the broadband sensor is centered directly over the nylon block at position 14



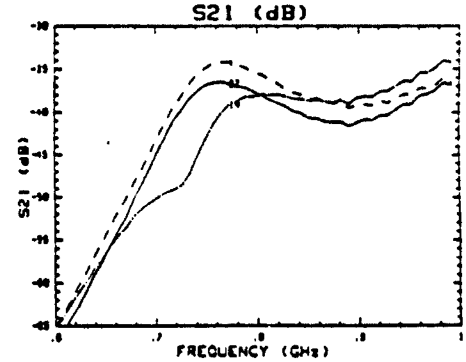
a) **Anomaly Depth = Flush**



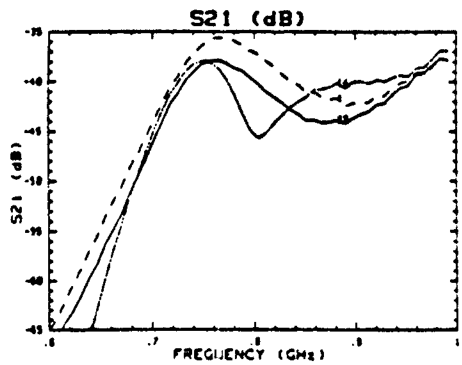
b) **Anomaly Depth = 3 inches**



c) **Anomaly Depth = 6 inches**

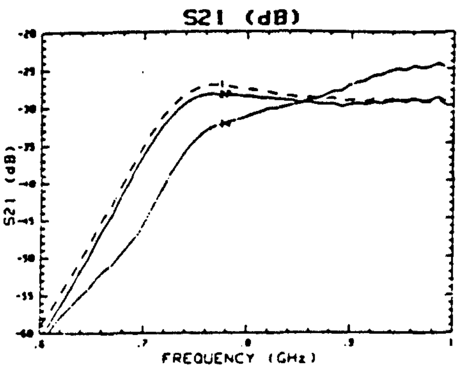


d) **Anomaly Depth = 9 inches**

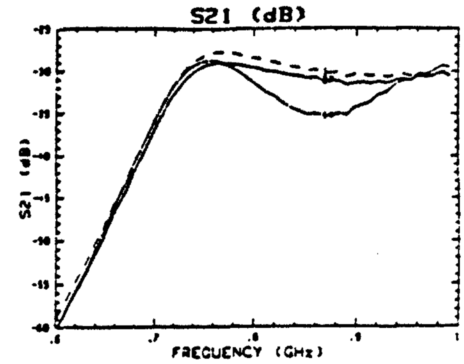


e) **Anomaly Depth = 12 inches**

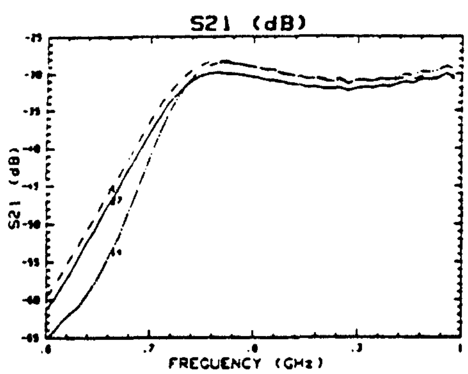
Figure 24. Measurement of transmission coefficient (S21) as a function of frequency over dry, loamy soil. In each figure, curves 1, 14, and 27 correspond, respectively, to the sensor head at the far left, center, and far right of a 39-inch horizontal scan. The broadband sensor is 5 inches above the soil. A nylon block (12 x 12 x 3 inches) is buried: **a)** flush; **b)** 3 inches; **c)** 6 inches; **d)** 9 inches; **e)** 12 inches with/below the soil surface so that the broadband sensor is centered directly over the nylon block at position 14



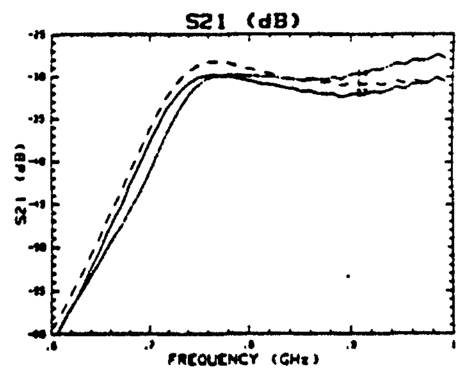
a) Anomaly Depth = Flush



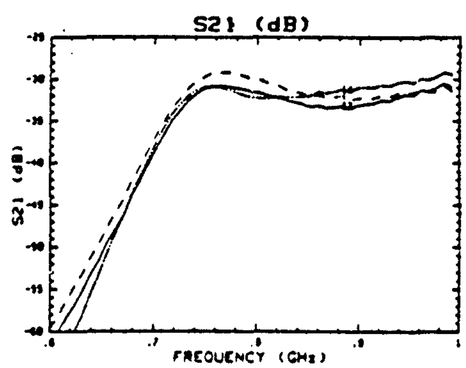
b) Anomaly Depth = 3 inches



c) Anomaly Depth = 6 inches

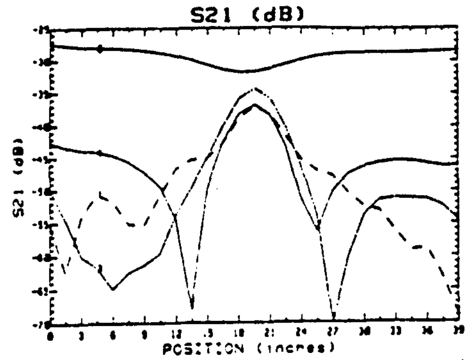


d) Anomaly Depth = 9 inches

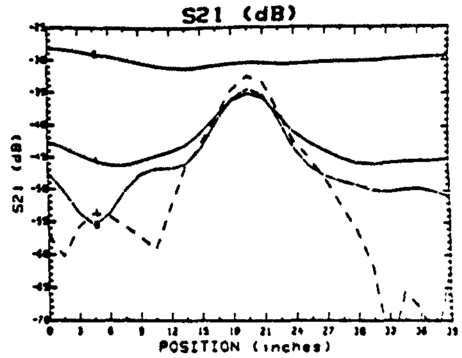


e) Anomaly Depth = 12 inches

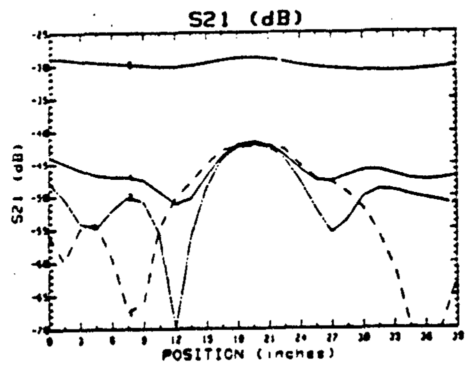
Figure 25. Measurement of transmission coefficient (S21) as a function of frequency over dry, loamy soil. In each figure, curved 1, 14, and 27 correspond, respectively, to the sensor head at the far left, center, and far right of a 39-inch horizontal scan. The broadband sensor is 6 inches above the soil. A nylon block (12 x 12 x 3 inches) is buried: **a)** flush; **b)** 3 inches; **c)** 6 inches; **d)** 9 inches; **e)** 12 inches with/below the soil surface so that the broadband sensor is centered directly over the nylon block at position 14



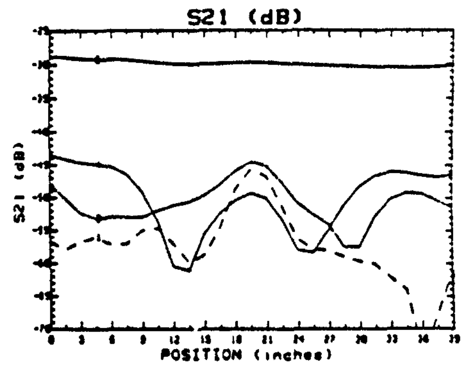
a) **Anomaly Depth = Flush**



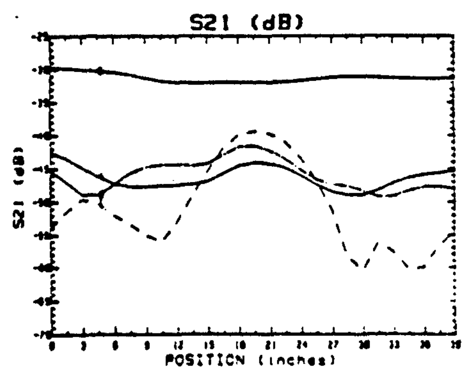
b) **Anomaly Depth = 3 inches**



c) **Anomaly Depth = 6 inches**

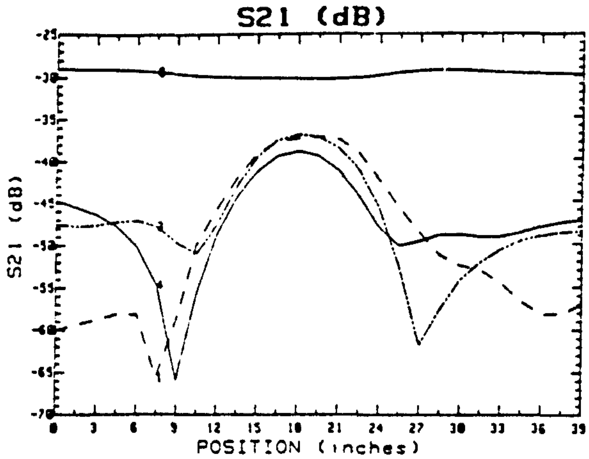


d) **Anomaly Depth = 9 inches**

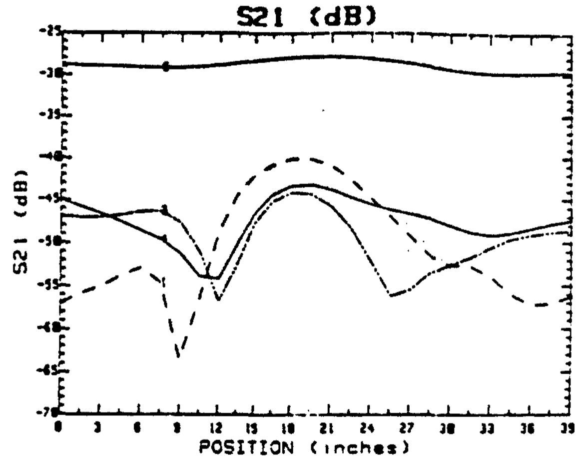


e) **Anomaly Depth = 12 inches**

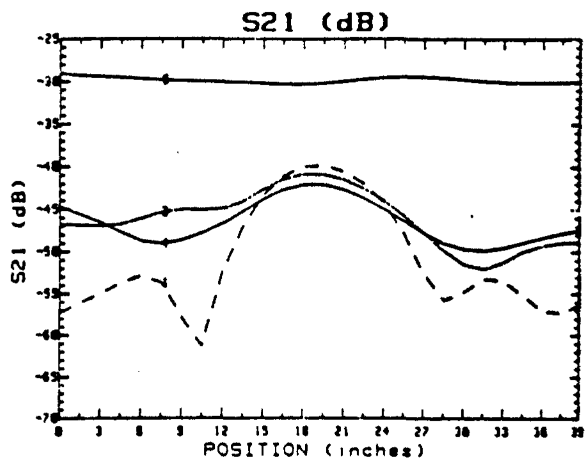
Figure 26. Measurement of transmission coefficient (S21) as a function of position for various sensor heights (1, 3, 4, and 6 inches as indicated) as the broadband sensor head is scanned over a nylon block (12 x 12 x 3 inches) buried: a) flush; b) 3 inches; c) 6 inches; d) 9 inches; e) 12 inches with/below the surface of dry, loamy soil. The transmission coefficient is measured at 796 MHz which is nearly resonant frequency of the broadband dipole. The receiving dipole passes over the nylon block first



a) Anomaly Depth = Flush

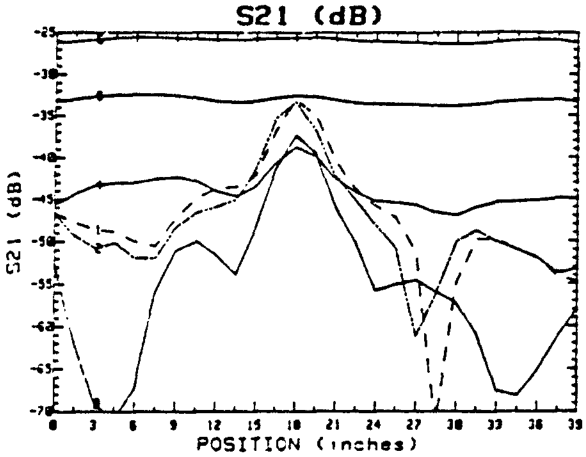


b) Anomaly Depth = 6 inches

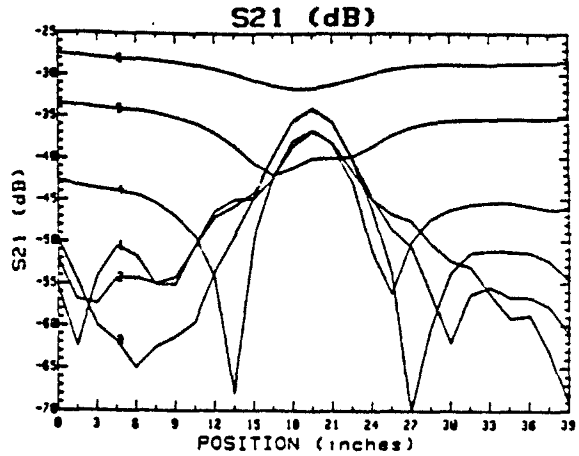


c) Anomaly Depth = 12 inches

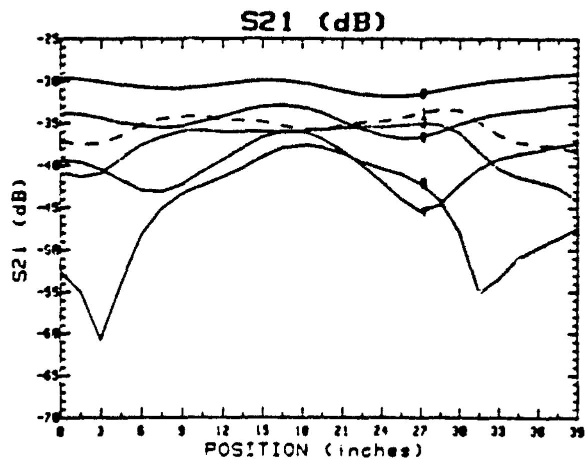
Figure 27. Measurement of transmission coefficient (S21) as a function of position for various sensor heights (1, 3, 4, and 6 inches as indicated) as the broadband sensor head is scanned over a nylon block (12 x 12 x 3 inches) buried: a) flush; b) 3 inches; c) 6 inches; d) 9 inches; e) 12 inches with/below the surface of dry, loamy soil. The transmission coefficient is measured at 796 MHz which is nearly resonant frequency of the broadband dipoles. The sensor head passes oriented so that the transmit and receive dipoles are parallel to the scan direction



a) Frequency = 1 GHz

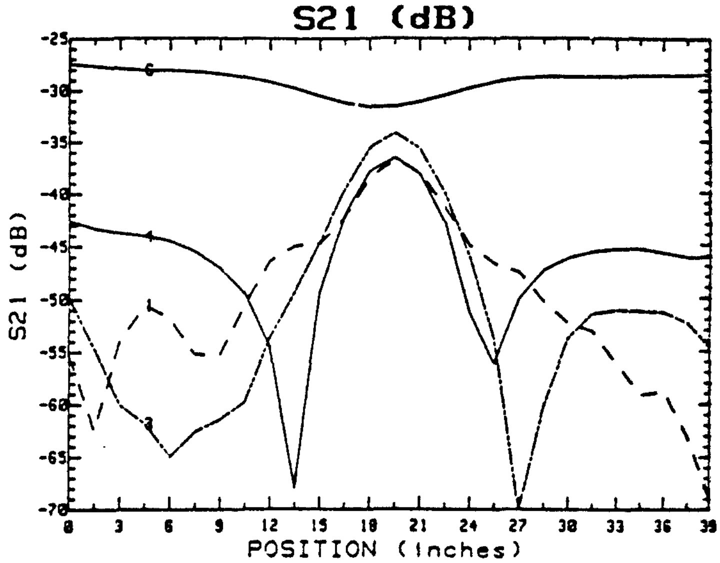


b) Frequency = 796 MHz

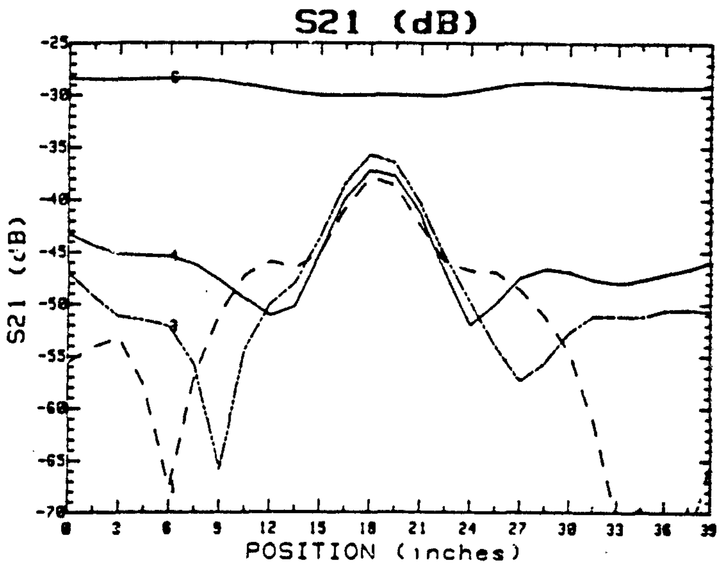


c) Frequency = 496 MHz

Figure 28. Measurement of transmission coefficient (S21) as a function of position for various sensor heights (1, 3, 4, and 6 inches as indicated) as the broadband sensor head is scanned over a nylon block (12 x 12 x 3 inches) buried flush with the surface of dry, loamy soil. The receiving dipole passes over the nylon block first. The transmission coefficient is measured near the resonant frequency of the broadband dipoles at: **a)** 1 GHz; **b)** 796 MHz; **c)** 496 MHz

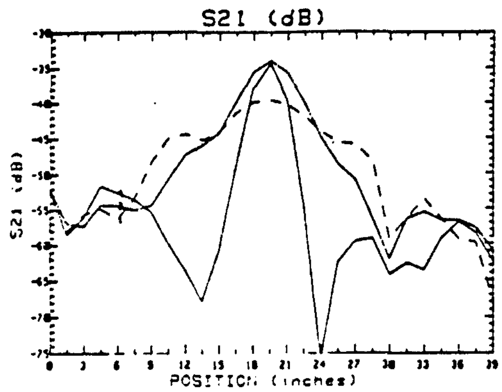


a) Broadband Dipole Sensor Head

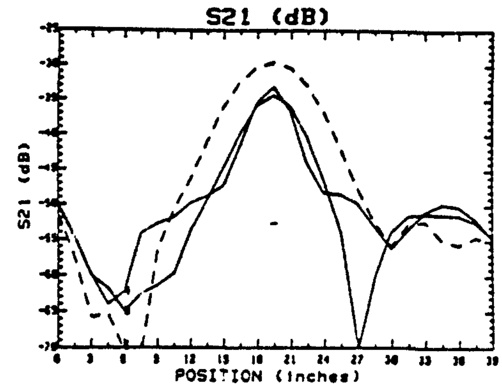


b) Printed Circuit (PC) Dipole Sensor Head

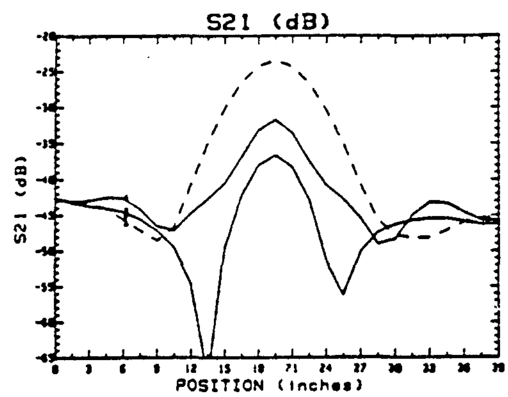
Figure 29. Measurement of transmission coefficient (S21) as a function of position for various sensor heights (1, 3, 4, and 6 inches as indicated) as the: a) broadband dipole; b) printed circuit (PC) dipole sensor head is scanned over a nylon block (12 x 12 x 3 inches) buried flush with the surface of dry, loamy soil. The transmission coefficient is measured at 796 MHz which is near the resonant frequency of the broadband and PC dipoles. In each case, the receiving dipole passes over the nylon block first



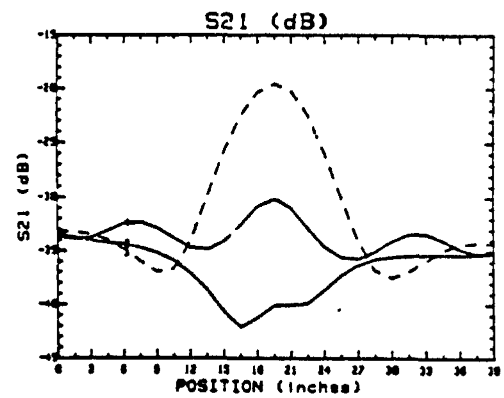
a) **Sensor Height = 2 inch**



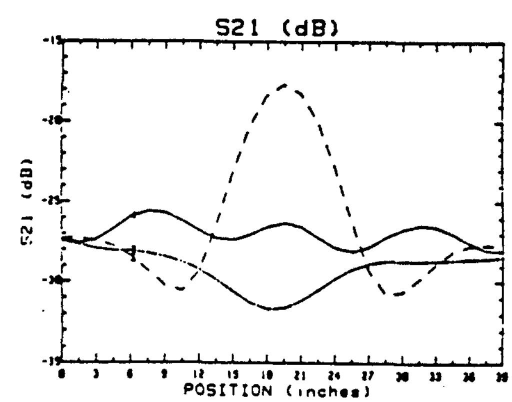
b) **Sensor Height = 3 inches**



c) **Sensor Height = 4 inches**



d) **Sensor Height = 5 inches**



e) **Sensor Height = 6 inches**

Figure 30. Measurement of transmission coefficient (S21) as a functicn of position for various anomalies, 1 - styrofoam, 3 - nylon, 4 - water, buried flush with the surface of dry loamy soil. The transmission coefficient is measured 796 MHz which is near the resonant frequency of the broadband dipoles. In each case, the receiving dipole of the sensor passes over the anomaly first. The sensor head is: **a)** 2 inches; **b)** 3 inches; **c)** 4 inches; **d)** 5 inches; **e)** 6 inches above the soil surface

APPENDIX B

COMPUTER CONTROL/DATA COLLECTION SOFTWARE

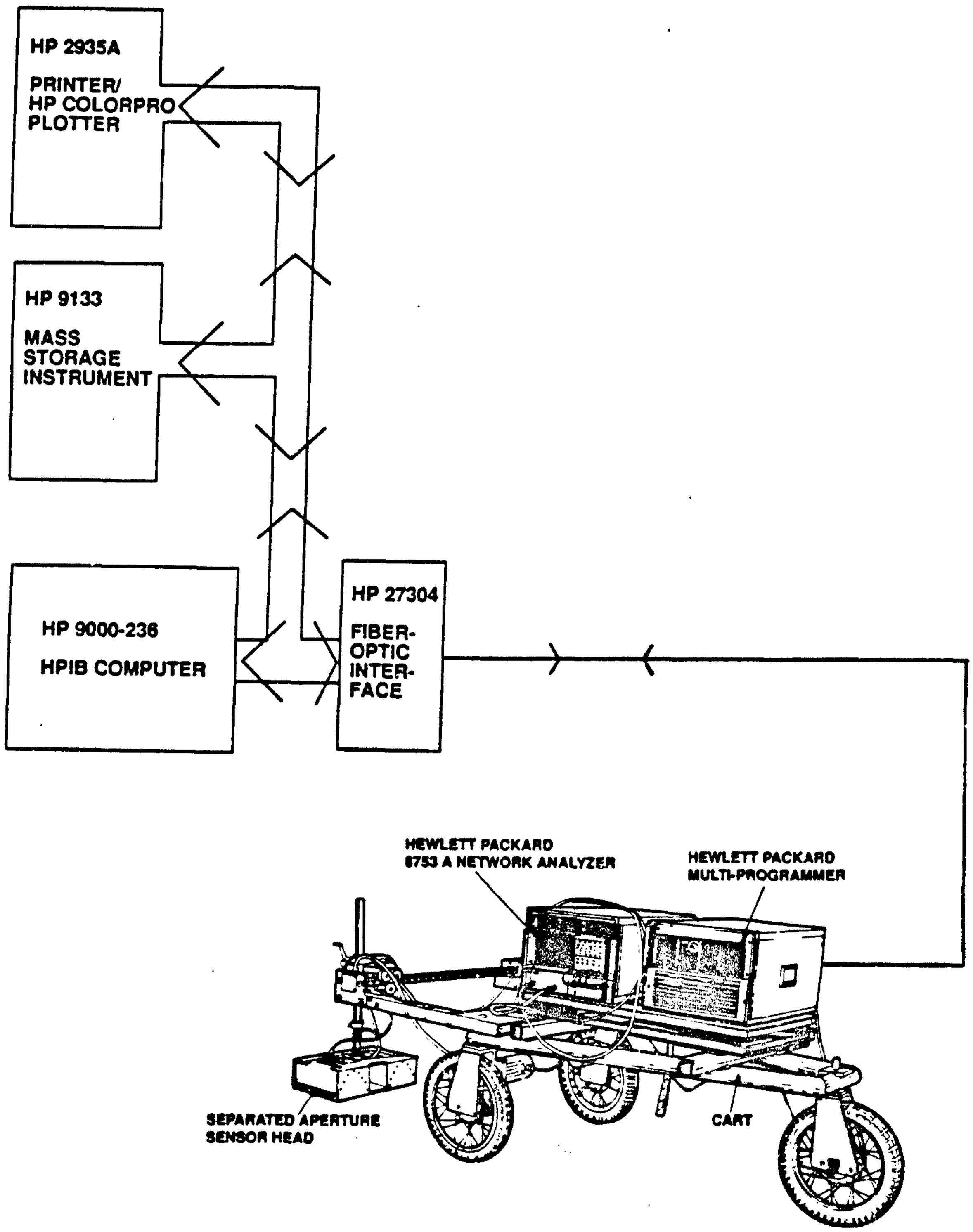
```
10   OPTION BASE 1
20   PRINTER IS 1
30   ASSIGN @Multi TO 723
40   DIM Dat(1:51,1:2)
50   INTEGER Hdr,Lgth
60   KEY LABELS OFF
70   CLEAR SCREEN
80   INPUT "MOVE CART BACKWARDS,OR FORWARDS, OR LEAVE STATIONARY?(B/F S)",Move$
90   Moveflag=0
100  IF Move$="B" OR Move$="F" OR Move$="S" THEN 190
110  CLEAR SCREEN
120  PRINT "INPUT ERROR."
130  PRINT "TRY AGAIN? (Y/N)"
140  INPUT Response2$
150  IF Response2$="Y" THEN 80
160  CLEAR SCREEN
170  PRINT "PROGRAM DISCONTINUED."
180  STOP
190  IF Move$="B" THEN GOSUB Backward
200  IF Moveflag=1 THEN 80
210  IF Move$="F" THEN GOSUB Forward
220  IF Moveflag=1 THEN 80
230  IF Move$="S" THEN 240
240  INPUT "MOVE ANTENNA TO RIGHT? (Y/N)",Answer1$
250  IF Answer1$="Y" OR Answer1$="N" THEN 330
260  PRINT "INPUT ERROR."
270  PRINT "TRY AGAIN? (Y/N)"
280  INPUT Response1$
290  IF Response1$="Y" THEN GOTO 240
300  CLEAR SCREEN
310  PRINT "PROGRAM DISCONTINUED."
320  STOP
330  IF Answer1$="N" THEN 370
340  Antflag=1
350  GOSUB Rgtant
360  Antflag=0
370  INPUT "IS THE WAVEGUIDE AT THE LEFT STOP? (Y/N)",Answ$
380  IF Answ$="Y" OR Answ$="N" THEN 470
390  PRINT "INPUT ERROR."
400  PRINT "TRY AGAIN? (Y/N)"
410  INPUT Response$
420  CLEAR SCREEN
430  IF Response$="Y" THEN GOTO 370
440  CLEAR SCREEN
450  PRINT "PROGRAM DISCONTINUED."
460  STOP
470  IF Answ$="Y" THEN 490
480  GOSUB Leftant
490  Flag=0
500  ABORT 7
501  OUTPUT 716;"POLA:"
510  CLEAR 716
520  OUTPUT 716;"S21;"
530  OUTPUT 716;"CENT 800 MHZ;"
540  OUTPUT 716;"SPAN 400 MHZ;"
550  OUTPUT 716;"MARK1 790 MHZ;"
560  OUTPUT 716;"POWE 20 DB;"
570  OUTPUT 716;"POIN 51;"
580  OUTPUT 716;"AVERO ON;"
590  OUTPUT 716;"NUMG16;"
600  OUTPUT 716;"AUTO;"
610  INPUT "IF CALIBRATED HIT ANY KEY TO CONTINUE.",Calgo$
620  INPUT "DISABLE PRINTER? TYPE THE LETTER D",Prntr$
```

```
630  IF Prntr$="O" THEN 681
640  INPUT "WHAT IS TODAY'S DATE? (MM/DD/YY)",Daysdate$
650  INPUT "WHAT WAVEGUIDE? NBS OR CUBIC: ",Waveguide$
660  INPUT "WHAT DIELECRIC MATERIAL IS BEING TESTED? ",Dielectric$
670  INPUT "HOW DEEP IS ANOMALY BURIED? (INCHES)",Dis$
690  PRINT "IS THIS TEST AN AREA SCAN OR A LINE SCAN OR"
691  PRINT "A FIXED POSITION SCAN (ASCAN/SCAN/FIXED)?"
700  INPUT Position$
710  IF Position$="ASCAN" OR Position$="SCAN" OR Position$="FIXED" THEN 800
720  CLEAR SCREEN
730  PRINT "INPUT ERROR."
740  PRINT "TRY AGAIN? (Y/N)"
750  INPUT Response$
760  CLEAR SCREEN
770  IF Response$="Y" THEN 680
780  PRINT "PROGRAM DISCONTINUED."
790  STOP
800  IF Position$="ASCAN" THEN Flag=2
810  IF Position$="FIXED" THEN
820  Flag=1
830  ELSE
840  CLEAR SCREEN
850  INPUT "WHAT IS HEIGHT OF WAVEGUIDE ABOVE GROUND? (INCHES)",Height$
860  END IF
870  CLEAR SCREEN
880  INPUT "WHAT ARE MEASUREMENT INCREMENTS? (INCHES)",Increments$
890  Increments=VAL(Increments$)
900  INPUT "HOW MANY READINGS ARE TO BE TAKEN?",Readings
910  Nmincrements$=VAL$(Readings)
920  IF Flag=2 THEN INPUT "HOW MANY INCREMENTS IS CART TO MOVE?",Scannbr
930  INPUT "NAME OF FILE?",One$
940  INPUT "READY TO COLLECT DATA? (Y/N)",Go$
950  IF Go$="Y" THEN 990
960  CLEAR SCREEN
970  DISP "PROGRAM HAS BEEN ABORTED."
980  STOP
990  IF Flag<>2 THEN 1050
1000 FOR J=37 TO Scannbr
1010 Column=Readings
1020 Rowckflag=0
1030 Rowcheck=J/2
1040 IF Rowcheck=INT(Rowcheck) THEN Rowckflag=1
1050 FOR I=1 TO Readings
1060 IF Flag=0 THEN 1070
1070 FOR Z=1 TO 10
1080 ON KEY Z LABEL "ABORT",1 GOTO 2770
1090 NEXT Z
1100 KEY LABELS ON
1110 ASSIGN @Dt TO 716;FORMAT OFF
1120 IF Flag=1 THEN
1130 INPUT "HIT ANY KEY TO PROCEED",Waits$
1140 OUTPUT 716;"NUMG16;AUTO;FORM3;OUTPDATA;"
1150 ELSE
1160 OUTPUT 716;"NUMG16;FORM3;OUTPDATA;"
1170 END IF
1180 ENTER @Dt;Hdr,Lgth,Dat(*)
1190 IF Flag=2 THEN
1200 IF Rowckflag=1 THEN
1210 Two$=VAL$(Column)     ! IF ROW IS EVEN NUMBER THEN COUNT BACKWARDS
1220 ELSE
1230 Two$=VAL$(I)
1240 END IF
1250 Four$=VAL$(J)
1260 Three$=One$&"R"&Four$&"C"&Two$
1270 ELSE
1280 Two$=VAL$(I)
```

```
1290  Three$=One$&"."&Two$
1300  END IF
1310  DISP "THIS IS FILE NAME  INCLUDING MEASUREMENT NUMBER): ",Three$
1320  CREATE BDAT Three$,5
1330  ASSIGN @Disc TO Three$
1340  OUTPUT @Disc;Hdr,Lgth,Dat(*)
1350  IF Prnter$="D" THEN 1640
1360  OUTPUT 716;"CLES;ESE2;"
1370  OUTPUT 716;"USER-SC PRINALL;"
1380  Stat=SPOLL(716)
1390  IF NOT BIT(Stat,5) THEN GOTO 1380
1400  SEND 7;TALK 16 CMD 9
1410  DISP "PRINTING CRT IMAGE FROM NETWORK ANALYZER"
1420  STATUS 7,3;Hpib
1430  IF NOT BIT(Hpib,6) THEN GOTO 1420
1440  PRINTER IS 701
1450  FOR K=1 TO 3
1460  PRINT CHR$(10)
1470  NEXT K
1480  PRINT "FILE NAME IS:  ",Three$
1490  PRINT "WAVEGUIDE IS: ",Waveguide$
1500  PRINT "DATE: ",Daysdate$
1510  IF Flag=0 THEN
1520  PRINT "WAVEGUIDE HEIGHT ABOVE GROUND IS :",Height$,"INCHES"
1530  ELSE
1540  PRINT "WAVEGUIDE HEIGHT ABOVE GROUND IS :",I,"INCHES"
1550  END IF
1560  PRINT "DIELECTRIC MATERIAL TESTED IS :",Dielectric$
1570  PRINT "POSITIONING OVER TARGET IS: ",Position$
1580  PRINT "RESOLUTION OF POSITIONING IS EVERY: ",Increments$,"INCHES"
1590  Increments=VAL(Increments$)
1600  PRINT "NUMBER OF MEASUREMENT INCEMENTS IS: ",Nmincrements$
1610  PRINT "THE DISTANCE FROM THE SOIL SURFACE TO THE TOP OF THE DIELECTRIC
              ANOMALY IS: ",Dis$,"INCHES"
1620  PRINT CHR$(12)
1630  PRINTER IS 1
1640  Column=Column-1
1650  IF I=Readings OR Position$="FIXED" THEN 1710
1660  IF Rowckflag=1 THEN
1670  GOSUB Leftant
1680  ELSE
1690  GOSUB Rghtant
1700  END IF
1710  NEXT I
1711  IF (J MOD 6)<>0 THEN 1720
1712  INPUT "IF DISC HAS BEEN CHANGED HIT ANY KEY TO CONTINUE",Go$
1720  IF Flag<>2 THEN 1760
1730  IF J=Scannbr THEN 1750
1740  GOSUB Cartmov
1750  NEXT J
1760  KEY LABELS OFF
1770  Distance=(Readings-1)*Increments
1780  DISP
1790  PRINTER IS 1
1800  CLEAR SCREEN
1810  PRINT "LAST MEASUREMENT HAS BEEN STORED. PROGRAM IS DONE."
1820  PRINT
1830  IF Position$="FIXED" THEN 1860
1840  PRINT "WAVEGUIDE HAS MOVED: ",Distance,"INCHES"
1850  KEY LABELS ON
1860  STOP
1870 Rghtant: !
1880           IF Antflag=1 THEN
1890           OUTPUT @Multi;"OP 6,35413,""  !HIGH CURRENT
1900           WAIT .3
1910           OUTPUT @Multi;"OP 6,6944,""  !MED CURRENT
```

```
1920          WAIT .2
1930          OUTPUT @Multi;"OP 6,65441,T"  !LOW CURRENT
1940          INPUT "HIT ANY KEY TO STOP",Stoptheant$
1950          GOSUB Stopant
1960          RETURN
1970          ELSE
1980          WAIT 1.0
1990          OUTPUT @Multi;"OP 6,65443,T"  !MED CURRENT
2000          WAIT .2
2010          OUTPUT @Multi;"OP 6,65441,T"  !LOW CURRENT
2020          WAIT .920
2030          GOSUB Stopant
2040          END IF
2050          Antflag=0
2060          RETURN
2070 Leftant: !
2080          IF Fc ckflag=1 THEN
2090          WAIT 1.0
2100          OUTPUT @Multi;"OP 6,65447,T"  !MED CURRENT
2110          WAIT .2
2120          OUTPUT @Multi;"OP 6,65443,T"  !LOW CURRENT
2130          WAIT .920
2140          GOSUB Stopant
2150          ELSE
2160          INPUT "HOW FAR FROM LEFT STOP IS WAVEGUIDE (INCHES)?",Inches
2170          Accumtime=(Inches-1.5)*1.13
2180          OUTPUT @Multi;"OP 6,65415,T"  !HIGH CURRENT
2190          WAIT .3
2200          OUTPUT @Multi;"OP 6,65447,T"  !MED CURRENT
2210          WAIT .2
2220          OUTPUT @Multi;"OP 6,65443,T"  !LOW CURRENT
2230          WAIT Accumtime
2240          GOSUB Stopant
2250          END IF
2260          RETURN
2270 Stopant: !
2280          OUTPUT @Multi;"OP 6,65534,T"
2290          RETURN
2300 Stopcart: !
2310          Refreshmenu=1
2320          OUTPUT 723;"OP 11,65526,T"
2330          OUTPUT 723;"OP 11,65522,T"
2340          DISP "CART STOPPED"
2350          RETURN
2360 Forward: !
2370          Moveflag=0
2380          FOR I=1 TO 8
2390          ON KEY I LABEL " STOP ",2 GOTO 2470
2400          NEXT I
2410          KEY LABELS ON
2420          DISP "CART MOVING FORWARDS"
2430          OUTPUT 723;"OP 11,65533,T"
2440          OUTPUT 723;"WC 8.2,4000T,WC 14.2,4000T"
2450          OUTPUT 723;"OP 2,5,14,5T"
2460          GOTO 2450
2470          GOSUB Stopcart
2480          DISP
2490          INPUT "MOVE CART SOME MORE? (Y/N)",Answer3$
2500          IF Answer3$="Y" THEN Moveflag=1
2510          RETURN
2520 Backward: !
2530          Moveflag=0
2540          FOR I=1 TO 8
2550          ON KEY I LABEL " STOP ",2 GOTO 2670
2560          NEXT I
2570          KEY LABELS ON
```

```
[illegible]
2590            OUTPUT 723;"OP 11,65519,T"
2600            OUTPUT 723;"WC 8.2,4000T,WC 14.2,4000T"
2610            OUTPUT 723;"OP 8,5,14,5T"
2620            GOTO 2610
2630            GOSUB Stopcart
2640            DISP
2650            INPUT "MOVE CART SOME MORE? (Y/N)",Answer3$
2660            IF Answer3$="Y" THEN Moveflag=1
2670            RETURN
2680 Cartmov: !
2690            INTEGER Scansiz,Scanden
2700            Cart_pulse=.003
2710            Scansiz=64
2720            Scanden=32
2730            Scanspc=DROUND(Scansiz/Scanden,3)
2740            Movecart(Scanspc,Cart_pulse)
2750            WAIT 1.5
2760            RETURN
2770  KEY LABELS OFF
2780  GOSUB Stopant
2790  DISP "PROGRAM ABORTED."
2900  KEY LABELS ON
2810  END
2820 Movecart: SUB Movecart(REAL Distance,Rate)
2830            IF Distance>0 THEN
2840            OUTPUT 723;"OP 11,65537,T"
2850            ELSE
2860            OUTPUT 723;"OP 11,65519,T"
2870            END IF
2880            OUTPUT 723;"WC 8.2,4000T,WC,14.2,4000T"
2890            FOR X=0 TO ABS(Distance) STEP Rate*5
2900            OUTPUT 723;"OP 8,5,14,5,T"
2910            NEXT X
2920            OUTPUT 723;"OP 11,65526,T"
2930            SUBEND
```



Block Diagram of Data Collection System

APPENDIX C
PLOTTING SOFTWARE

```
10   !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
20   !                                                                !!
30   !                  This program is designed                     !!
40   !    to  extract,convert, and plot data collected in real and  !!
50   !!    imaginary number..                                        !!
60   !                                                                !
70   !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
80   OPTION BASE 1
81   PRINT "WELCOME TO THE R&I PLOTTING PROGRAM FOR HP DATA!!"
90   Mes..                        !preliminary set for line labeling
100  INTEGER Lt(7),Hdr,Lgth
110  DIM Bat(151,1:2),Ary(27,6)
120  Xmarkms.
130  Nfp=25                       !the # out of 51 that is plotted per position
140  INPUT "HOW MANY FILES ARE TO BE PLOTTED?",Sk
171  LINPUT "PRINT ON PLOTTER? (Y/N)",Ipltr$
172  INPUT "WHAT IS THE DESIRED SCALE FOR Y-AXIS?  MINM....?",Ymin
173  INPUT "                                       MAXM.....?",Ymax
180  FOR Kt=1 TO Sk              !THE # OF FILES (LINES) PLOTTED
181  LINPUT "WHAT IS THE ROOT FILE TO BE PLOTTED NEXT?",Filname$
182  INPUT "PLEASE INSERT DISK",Junk$
183  PRINT "Extracting data.  Please stand by."
190  FOR Kn=1 TO 27              !The # of positions to be plotted
200  Pdat$=Filname$&VAL$(Kn)
210  ASSIGN @File TO Pdat$        !
220  ENTER @File;Hdr,Lgth,Bat(*)  !
230  ASSIGN @File TO *            ! Data extraction
240  Ary(Kn,Kt)=Bat(Nfp,1)        !
250  Ary(Kn,Kt)=Bat(Nfp,2)        !
260  Rncd=Bat(Nfp,1)
270  Incd=Bat(Nfp,2)
280  Zcd=10*LGT(Rncd^2+Incd^2)     converting from r&i # to reals
290  Ary(Kn,Kt)=Zcd               !10 LOG (X^2 +Y^2) =.........
300  NEXT Kn
310  NEXT Kt
320  DIM C1(7)
330  DATA 1,3,4,6,5,6
340  READ C1(1),C1(2),C1(3),C1(4),C1(5),C1(6)
350  DATA 4,3,2,5,8,1
360  READ Lt(1),Lt(2),Lt(3),Lt(4),Lt(5),Lt(6)
370  DATA S21 (dB),POSITION (inches),S21 (dB)
390  READ Title$,Xlabel$,Ylabel$ ! TITLE OF PLOT, X LABEL, YLABEL
400  DATA 0.,39.
410  READ Xmin,Xmax               ! MINIMUM X VALUE, MAXIMUM X VALUE, ETC.
420  DATA 1.5,1.,2,5
430  READ Xinc,Yinc,Xnt,Ynt ! X-AXIS SMALL TICK INCREMENT, Y-AXIS SMALL TICK
440  ! INCREMENT, NUMBER OF TICKS BEFORE A MAJOR TICK IN X-DIRECTION
450  !NUMBER OF TICKS BEFORE A MAJOR TICK IN Y-DIRECTION
460  DATA 3.,5.
470  READ Xhgl,Yhgl ! INCREMENT BETWEEN GRID LINES IN X DIRECTION,  ETC.
480  DATA 0.,39.,1.5
490  READ Xdatamin,Xdatamax,Xdelta   ! VALUES OCCUR IN PLOT FILE EVERY XDELTA
500  ! STARTING WITH XDATAMIN AND ENDING WITH XDATAMAX
510  DATA 5
520  READ N ! NUMBER OF FILES TO BE READ IN, FOLLOWED BY THE NAME OF THE FILES
530  ! WHICH ARE TO BE READ IN. THE FILES ARE READ IN BELOW IN THE PLOT LOOP
540  C$=CHR$(255)&"K"
550  OUTPUT 2 USING "#,K";C$    ! CLEAR LEFTOVER DISPLAY
560  PRINT
570  PRINT "VIEW GRAPH AS LONG AS YOU WISH"
580  PRINT "PRESS THE SPACEBAR TO GET BACK TO THE BASIC SYSTEM"
```

```
590   INPUT G$ ! LET USER VIEW MESSAGES
600   ON KEY GOTO 1350 ! PROVIDE EXIT
610   OUTPUT 2 USING "#,K";C$ !CLEAR SCREEN FOR GRAPH
620   GINIT ! INITIALIZE VARIOUS GRAPHICS PARAMETERS
630   IF Iplt$="N" THEN
640   PLOTTER IS CRT,"INTERNAL" ! USE THE INTERNAL SCREEN
650   ELSE
660   PLOTTER IS 705,"HPGL" ! USE THE COLORPRO HP PLOTTER
670   END IF
680   GRAPHICS ON ! TURN ON THE GRAPHICS SCREEN
690   LORG 6     REFERENCE POINT : CENTER OF TOP OF LABEL
700   X_gdu_max=100*MAX(1,RATIO)  DETERMINE HOW MANY GDUS WIDE THE SCREEN IS
710   Y_gdu_max=100*MAX(1,1/RATIO) ! DETERMINE HOW MANY GDUS HIGH THE SCREEN IS
720   FOR I=-.3 TO .3 STEP .1  OFFSET OF X FROM STARTING POINT
730   MOVE X_gdu_max/2+I,.95*Y_gdu_max !MOVE TO ABOUT MIDDLE OF TOP OF SCREEN
740   LABEL Title$ ! WRITE TITLE OF PLOT
750   NEXT I ! NEXT POSITION FOR TITLE
760   DEG ! ANGULAR MODE IS DEGREES (USED IN LDIR)
770   LDIR 90 ! SPECIFY VERTICAL LABELS
780   CSIZE 3.5  ! SPECIFY SMALLER CHARACTERS
790   MOVE .13*X_gdu_max,Y_gdu_max/2 ! MOVE TO CENTER OF LEFT EDGE OF SCREEN
800   LABEL Ylabel$ ! WRITE Y-AXIS LABEL
810   LORG 4     REFERENCE POINT: CENTER OF BOTTOM OF LABEL
820   LDIR 0 ! HORIZONTAL LABELS AGAIN
830   MOVE X_gdu_max/2,.13*Y_gdu_max !X: CENTER OF SCREEN; Y: ABOVE KEY LABELS
840   LABEL Xlabel$  WRITE X-AXIS LABEL
850   VIEWPORT .20*X_gdu_max,.80*X_gdu_max,.2*Y_gdu_max,.8*Y_gdu_max
860   ! DEFINE SUBSET OF SCREEN AREA
870   WINDOW Xmin,Xmax,Ymin,Ymax !ANISOTROPIC SCALING: LEFT/RIGHT/BOTTOM/TOP
880   AXES Xinc,Yinc,Xmin,Ymin,Xmt,Ymt,3 !DRAW AXES INTERSECTING AT LOWER LEFT
890   AXES Xinc,Yinc,Xmax,Ymax,Xmt,Ymt,3 !DRAW AXES INTERSECTING AT UPPER RIGHT
900   !GRID Xhgl,Yhgl,Xmin,Ymin,1,1 !DRAW GRID WITH NO MINOR TICKS
910   CLIP OFF ! SO LABELS CAN BE OUTSIDE VIEWPORT LIMITS
920   CSIZE 2.5,.5 ! SMALLER CHARTS FOR AXIS LABELLING
930   LORG 6 ! REF PT: TOP CENTER
940   Xmax=Xmax-Xhgl
950   Xmaxx=Xmax
960   FOR A=Xmin TO Xmaxx STEP Xhgl ! EVERY XHGL UNITS
970   MOVE A,Ymin-.01*ABS(Ymin) ! A SMIDGEON BELOW X-AXIS
980   LABEL USING "#,K";A ! COMPACT; NO CR/LF
990   NEXT A ! ET SEQUENS
1000  LORG 8 ! REF. PT: RIGHT CENTER
1010  Xmin=.6
1020  WINDOW Xmin,Xmax,Ymin,Ymax
1030  Ymaxx=Ymax-Yhgl
1040  Ymax=Ymax
1050  FOR I=Ymin TO Ymaxx STEP Yhgl ! EVERY YHGL
1060  MOVE Xmin-.01*ABS(Xmin),I !SMIDGEN LEFT OF Y AXIS
1070  LABEL USING "#,K";I ! COMPACT; NO CR/LF
1080  NEXT I ! ET SEQUENS
1090  Xmin=0.
1100  WINDOW Xmin,Xmax,Ymin,Ymax
1110  CLIP ON
1120  PENUP  LABEL STATEMENTS LEAVES THE PEN DOWN
1130  FOR Kn=1 TO N
1140  LINE TYPE Ltype(Kn)
1150  K=0
1160  FOR X=Xdatamin TO Xdatamax STEP Xdelta ! POINTS TO BE PLOTTED..
1170  K=K+1
1180  IF K<=N THEN PLOT X,Array(K,Kn) ! GET A DATA POINT AND PLOT IT AGAINST X
1190  NEXT X
1200  LORG 2
1210  Kk=0
1220  FOR X=Xdatamin TO Xdatamax STEP Xdelta
1230  Kk=Kk+1
1240  IF X>Xmark-Xdelta AND X<Xmark+Xdelta THEN
```

```
1250  LINE TYPE 1
1260  MOVE X,Hry(X,1,Kn)
1270  LABEL Mes                    !labels for each line (see line 90)
1280  Mes=Mes+1
1290  END IF
1300  NEXT X
1310  PENUP
1320  WAIT 2
1330  NEXT Kn
1340  GOTO 1340
1350  GRAPHICS OFF
1360  OUTPUT 2 USING "#,K";CS
1370  PRINT "THE DEMO IS COMPLETE. YOU CAN USE THE BASIC SYSTEM AGAIN.
1380  END    !  FINIS
```

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